Golder Associates Ltd.
CONSULTING ENGINEERS

REPORT

TO CANMET

ON

A REVIEW AND EVALUATION OF MICROSEISMIC MONITORING TECHNIQUES SYDNEY COALFIELD, NOVA SCOTIA

DSS CONTRACT NO. 23440-9-9013

Distribution:

15 copies - CANMET (Cape Breton Coal Research Laboratory)
Sydney, Nova Scotia

3 copies - Golder Associates
Mississauga, Ontario

MICROMEDIA

226 pp

September 1990

891-1736

GOLDER ASSOCIATES LTD. • 2180 MEADOWVALE BLVD., MISSISSAUGA, ONTARIO, CANADA L5N 5S3 • TELEPHONE (416) 567-4444 • TELEX 06-218812 • FACSIMILE (416) 567-6561

OFFICES IN CANADA • UNITED STATES • UNITED KINGDOM • SWEDEN • AUSTRALIA

TABLE OF CONTENTS

		Page No.
ABSTRACT		v
1.	INTRODUCTION	1
2.	OUTBURST PHENOMENIA ASSOCIATED WITH MINING	3
2.1	Introduction to the Outburst Phenomena	5
2.2	Outburst in the Sydney Coalfield	8
2.2.1	An Outburst Initiation Model for the Sydney Coalfield	12
3.	AN OVERVIEW OF MICROSEISMIC MONITORING IN MINING	14
3.1	The Methodology of Microseismic Monitoring	14
3.2	Overview of System Development for Coal Mining Applications	18
3.3	An Overview of Systems Developed for Hard Rock Applications	29
3.4	Microseismic Monitoring Systems for Evaporite Mining Applications	38
3.5	Systems of Relevance to the Sydney Coalfield	40
3.6	Seismic Tomographic Imaging	51
3.6.1	Combined Tomographic Imaging and Microseismic Monitoring at Strathcona Mine	53
4.	SYSTEM DESIGN	55
4.1	Design Criteria	57
4.2	Appraisal of the Applicability of the Systems to the Outburst Phenomenon in the Sydney Coalfield	74
4.3	Desgin of Microseismic Monitoring System for the Sydney Coalfield	78
4.3.1	Monitoring the Mine Environment	78
4.3.1.1	Deployment of Transducer Arrays	79
4.3.1.2	Surface Processing and Analysis System	86
4.3.2	Detailed Panel-Based Monitoring	87
4.3.2.1	Underground Acquisition System	89
4.3.2.2	Geophone Layout	89
4.3.2.3	Surface Processing and Analysis System	92
4.3.2.4	Channel-Wave Seismology	93
5.	CONCLUSIONS AND RECOMMENDATIONS	97

TABLE OF CONTENTS CONT.

TABLES 1 - 3

FIGURES 1 - 10

APPENDIX A Detailed Review of Previous Development and Operation of Microseismic Networks in Different Countries A1-62

REFERENCES

LIST OF TABLES

1. Outburst - Prone Areas of the World

2. Statistics of the Worst Outbursts

3. Distribution of Outbursts in the Gwendraeth Valley to 1 August 1986

LIST OF FIGURES

1. Location Map of Sydney Coalfield, Nova Scotia

2. Possible Locations for Geophones Packages for Lingam Colliery

3. Block Diagram for a "Divo" Unit, a Four Channel Acquisition Module

4. Block Diagram of a "Slave" Unit, Which Receives Data from the Divo Units and Applies Filters

5. Block Diagram of the Complete Mesas Seismo-Acoustic System, Showing Equipment Above and Below Ground

6. Typical Geophone Layout for a Detailed Panel Based Monitoring System

7. Event Density Diagram and Locations of Destressing Blasting

8. The Source Locations of Events Caused By Mining

9. Stacked Dispersion Curves for the First Love Wave Mode

10. Dispersion Curves and Hilbert Transform of a Typical Channel Wave

ABSTRACT

During the operating life of the No. 26 Colliery of the Sydney Coalfield violent dynamic phenomena described as rock and gas outbursts occurred whenever sandstone erosion channels were located within 2.7m above the coal seam.

Although the No. 26 Colliery has since closed the problem is considered serious and research has continued. This report forms a part of this continuing research programme, addressing the discipline of microseismic monitoring techniques to the prediction of rock and gas outbursts within the Sydney Coalfield.

The outburst phenomenon is discussed, which includes a discussion of the interaction between coal and gas. Brief definitions of catastrophic mine failures are also included. Both the type of gas and the states in which it can exist are also referred to along with their postulated associated effects. The association between outbursts and structure is also highlighted. There exists, on a worldwide basis, documentary evidence showing the relationship between outbursts and sedimentary features. A review of the work undertaken on the outburst occurrences at the No. 26 Colliery is included and parallels are drawn between the outbursts experienced in the Sydney Coalfield and those in other countries.

An overview of a detailed review of microseismic/acoustic monitoring instrumentation and techniques is presented, the detailed review being presented as an Appendix. The overview summarises the systems identified as applied to coal mining, hard rock mining and evaporite deposit mining. This also includes an assessment of systems relevant to the Sydney Coalfield. The detailed review, included as an Appendix has been sub-divided, based upon the deployment of the transducers.

The review systematically documents the available information on systems developed and installed within the relevant country, under the deployment headings. Where possible the review includes the full description of the instrumentation, including data acquisition, software and the performance of the systems. The suitability of the systems and the philosophies is also discussed. There is very little information available as to the costs of the system, but where this has been reported it has been included.

Although not strictly within the scope of work, a review of the potentially beneficial tool of Seismic Tomographic imaging is also included. The technique can be used to delineate zones where stress concentrations occur which can, in specific instances, be related to sedimentary structures, and can be indicative of areas that are possibly more prone to outburst.

In developing a detailed methodology the design criteria are discussed, from transducer selection and site selection through transmission systems, signal conditioning, data acquisition, both computer based and recorder based to processing hardware and software. An appraisal of the applicability of the systems to the outburst phenomena in the Sydney Coalfield is again discussed prior to a discussion of a system. This includes transducer selection and deployment, a transmission system and data acquisition and processing hardware. Final decisions on transducer type can only be made after a field trial of a pilot study, to determine the frequency range and attenuation charactertics. Attention is also drawn to some of the specialised software required. This includes the use of the only identified commercially available system to monitor a section of the mine environment.

A micro-seismic system has been designed for use within the Sydney Coalfield, which has been broadly divided into two sections. An overall mine environment monitoring system, with large inter-geophone spacings and a 'surface' component. The second section utilises local arrays with small inter-geophone spacings for detailed panel-based monitoring. The transmission systems for the data is also described. Data acquisition is based around a UNIX based workstation and also digital data recorders. Specialized software requirements are also highlighted.

RÉSUMÉ

Des phénomènes dynamiques violents ont marqué les opérations de la houillère no 26 du bassin charbonnier de Sydney. Ces phénomènes décrits comme coups de toit et coups de grisou, surviennent aussitôt que les canaux d'érosion dans le grès sont à moins de 2.7 m au-dessus de la couche de charbon.

Quoique la houillère no 26 a cessé ses opérations, le problème est considéré sufissamment sérieux pour que les recherches se poursuivent. De ce programme de recherche a été produit ce rapport traitant des techniques de surveillance microséismique pour la prédiction des coups de toits et de grisou dans le bassin charbonnier de Sydney.

Ce rapport présente une discussion sur le phénomène des coups de toit et de grisou et l'interaction entre le charbon et le gaz, une brève définition des types de rupture catastrophiques minières, les types de gaz avec leur différents états et effets possibles. Le lien entre les coups de toit et de grisou et la structure géologique est aussi traité. Des évidences existent dans la littérature, et ce sur une échelle mondiale, montrant une relation entre ces phénomènes et les caractéristiques sédimentaires des roches. Le rapport fournit une revue des travaux entrepris sur l'étude de la fréquence observée des coups de toit et de grisou à la houillère no 26 de même qu'une comparaison avec les fréquences dans le bassin charbonnier de Sydney en général et dans d'autres pays.

De plus, un survol de l'instrumentation de surveillance microséismique/acoustique et des techniques est présenté. Ce survol identifie les systèmes jugés applicables aux houillères, aux mines métalliques et aux

dépôts d'évaporite, et évalue les systèmes appropriés pour le bassin charbonnier de Sydney. La revue détaillée, présentée en annexe, a été subdivisée sur la base des différents senseurs disponibles.

La revue documente de façon systématique l'information sur les systèmes développés et installés à l'intérieur de la région étudiée. Lorsque possible, la revue fournit une description complète de l'instrumentation, du système d'acquisition de données, des logiciels et de la performance des systèmes. Il n'y a que très peu d'information disponible sur le coût des systèmes, lorsque disponible elle est ajoutée.

Quoique pas nécessairement à l'intérieur de la portée des travaux, une revue de l'imagerie séismique tomographique (Seismic Tomographic Imaging), un outil possiblement très intéressant, est ajoutée. Cette technique peut être utilisée pour déterminer les zones de concentration de contraintes, pouvant dans certains cas se rapporter à des structures sédimentaires, et pouvant indiquer les régions les plus propices aux coups de toit et de grisou.

Dans le but de développer une méthodologie détaillée, les critères de conception sont discutés, et ce, de la sélection des senseurs et du site, en passant par les systèmes de transmission, le conditionnement des signaux, l'acquisition des données sur ordinateur et sur système d'enregistrement, jusqu'au système de traitement et des logiciels. L'applicabilité du système au cas particulier du bassin charbonnier de Sydney est évaluée avant sa présentation. Elle comprend le choix des senseurs et de leur localisation, du système de transmission et d'aquisition de données.

Les décisions finales au sujet du type de senseurs à utiliser peuvent seulement être faites après un essai de chantier faisant partie d'une étude pilote pour déterminer le champ de fréquence et l'atténuation rencontrée. Une attention est aussi accordée aux logiciels spécialisés nécessaires et au seul système commercialement disponbile pour surveiller une partie de l'environnement de la mine.

Un système micro-séismique a été conçu pour être utilisé dans le bassin charbonnier de Sydney. Ce système est divisé en deux (2) composantes principales. La première composante comprend l'ensemble du système de surveillance environnementale de la mine composé de géophones sous-terre très espacés et à la surface. La deuxième composante utilise des rangées avec petits espacements entre les géophones pour la surveillance locale (panel-based) détaillée. Le système de transmission pour les données est aussi décrit. L'acquisition de données se fait à partir d'une station de travail UNIX et aussi sur un système d'enregistrement digital de données. Les exigences particulières des logiciels sont aussi présentés.

1. INTRODUCTION

A long term research program is being undertaken by the Coal Research Laboratory of the Canada, Centre for Mineral and Energy Technology (CANMET) to study the problem phenomena of rock and gas outbursts. As a continuation of this research program Golder Associates Ltd. has been awarded a research contract under the auspices of CANMET on behalf of the Department of Supply and Services to review and evaluate micro-seismic monitoring techniques for outburst prediction in the Sydney Coalfield, Nova Scotia.

The No. 26 Colliery, was in operation until April 1984, when a fire caused the closure of the mine. Development headings in virgin coal, using drilling and blasting, were subject to violent dynamic phenomena (described as rock and gas outbursts) whenever sandstone erosion channels were located within 2.7m of the top of the coal seam. It was considered that workings in other operating mines in the Sydney Coalfield could encounter similar conditions as they reach greater depths in their mining operations.

Drilling programs in the deeper underground mines of the Sydney Coalfield are being carried out by CBDC with an attempt to identify sandstone erosion channels which might potentially cause the initiation of rock and gas outburst events. In conjuction with the field investigation a review and evaluation of the available microseismic monitoring techniques for outburst prediction in the Sydney Coalfield was considered to be relevant to the overall research program of rock and gas outburst phenomena.

As part of this research contract a detailed worldwide review of microseismic monitoring systems has been undertaken. In general, rock and gas outbursts are restricted in their occurrence and geographical distribution and, as a result, little work has been conducted for the prediction of such events. Most work on microseismic monitoring is inevitably being concentrated on the rockburst phenomena. In addition, as a consequence of the events perturbing the working areas, the majority of the effort directed towards monitoring systems for the detection of catastrophic failures has been for the development of underground systems, rather than surface systems. This has tended to bias the proceeding review to such underground systems. However, for a rigorous system to be developed, it is considered that microseismic stations should be located at varying depths within the mine and at a variety of surface sites, where applicable.

The review of microseismic systems has been divided into sections, based on their disposition within the mine environment. Also, a very brief review of one case study of tomographic imaging has been included. Although the discussion of this method is outside the scope of work for this study, its applicability to the prevailing conditions justifies its inclusion.

Based on discussions held with the Cape Breton Development Corporation (CBDC) and CANMET as to their requirements, two microseismic monitoring systems have been designed. These systems include a network to monitor the whole mine environment, which can also be used to target the deployment of the second system, a panel based monitoring system if outburst conditions are indicated

2. OUTBURST PHENOMENA ASSOCIATED WITH MINING

Outbursts have been a major problem in coal mining for many decades, although their occurrence is increasing as both mining depths and extraction rate increase.

In simplistic terms rock failures in mines fall into four main categories.

- rock falls
- rockbursts
- bumps
- outbursts

Rock falls are self explanatory, and occur when loosened rock falls, mainly under its own weight and clearly can occur in any mining environment. Rockbursts are violent failures of rock which may cause significant damage to the excavation, similarly, it is considered that bumps are also violent failures, but the resulting damage is less and in some cases they are considered to cause no damage. Outbursts are usually driven by a rapid release of gas which causes rock material, often coal, to be ejected into the excavation.

Rockbursts and bumps usually occur in deep metalliferous mines in which thin tabular deposits in strong, brittle siliceous rocks of igneous or metamorphic origin are worked. The seismicity associated with such mining appears to have many features in common with those of natural earthquakes (Cook, 1976). Rockbursts are not, however, confined to metalliferous mines and have been reported from coal mines in Poland (Matuszewski, 1980) and bumps described as coal bumps have been reported from the USA and France.

Outbursts, in simple terms are a stress related phenomenon exacerbated by the presence of gas. In some cases the pressure of the confined gases and their desorption rate appear to be the dominant factors that culminates in failures. Whereas in other cases very little gas is involved and a complex relationship of stresses and strains over and above those naturally present in the rocks is responsible for the outburst, such an outburst is more typical of the rockbursts experienced in hard rock mining. In general outbursts appear to be restricted to sedimentary sequences of 'soft rocks', and are usually associated with coals and evaporite deposits. The term outburst appears to be applied to a series of failure types and it could be said that the two end members of the series are coal bursts and gas outbursts with rock/gas outbursts being between these two end members. The coal bursts of the Miike Coal Mine, Japan (Kaneko et. al., (in press)) for example, have occurred with no associated gas and would be considered to be more typical of a rockburst, however, these events are considered to fall within the outburst category. It would appear from this that the role played by the gas in outbursts increases from coal bursts through the series to gas outbursts. At the other extreme very little rock material is expelled and the outburst product consists pre-dominantly of gas.

An instantaneous outburst of coal and gas in a coal mine may be defined as, (Shepherd et. al., 1981):-

> 'a spontaneous rejection of coal and gas from the solid where the coal is invariably comminuted and the gas in a mixture of methane and carbon dioxide. An outburst results in a cavity ahead of or to one side of the working place and usually originates in the face within the upper section of the working profile. Large quantities of gas are emitted and there is

usually a rapid reduction in the emission rate with time.'

Where gas plays a dominant role in the outburst, the large volumes of powdery coal and dust produced may 'flood' the working areas and surrounding roadways for many metres almost to the roof, with a small gap, the gas escape channel remaining under the roof. Where the stresses are the predominant cause, the material ejected is in larger blocks and is often thrown out from a conical cavity.

Related phenomenon often occur, including rockbursts and bumps. These usually do not involve gas as a driving mechanism although it is often emitted and consequently there is often no pneumatic transport of the burst material. As such these are predominantly stress related.

2.1 Introduction to the Outburst Phenomena

Catastrophic seismic events are a recurrent problem in mineral and coal mining, although most research has concentrated on rockbursts rather than outbursts. Instantaneous outbursts are a major hazard to mining in many parts of the world, resulting in the disruption of mining and have been the cause of many fatalities. Fortunately, there was no reported loss of life in any of the outburst events that occurred in No. 26 Colliery, despite the varying degree of damage to the installed support and disruptions the mining operation.

Outbursts are instantaneous catastrophic failures of the coal mine structure, characterised by emissions of large quantities of finely divided coal-dust and gas (the principal gas being methane although in some parts of the world carbon dioxide is predominant) from a coal face. Outbursts are a global problem with occurrences in

Australia, Canada, China, Europe, Eastern Europe, Japan, the USA and the USSR. Table 1 summarises the outburst prone areas of the world with Table 2 reporting the worst incidents from those countries.

Simplistically, outbursts are a stress related phenomenon exacerbated by the presence of gas in large quantities within the seam. The outburst mechanism is complex, as a consequence of the many parameters that have a bearing on the phenomenon. Although outbursts are generally associated with coal, they have occurred in other rock types, for example in potash mines at Boulby (Cleveland Potash) in the United Kingdom and salt in Louisiana (Belle Isle Mines, New Iberia) and in East Germany.

Outbursts are particularly frequent in coal, as a consequence of the nature of the interaction between coal gases and the coal matrix. Coal has the capacity to adsorb large quantities of methane, carbon dioxide or both onto the coal surfaces. Coal gas can be a mixture of carbon dioxide and methane, with one component predominating. However, other gases are sometimes found in coal seams, such as nitrogen and hydrogen sulphide. The coal gas in the Sydney Coalfield comprises predominatly methane (75 - 80%) with nitrogen, ethane, carbon dioxide and other hydrocarbons in relatively small quantities. In the Bowen and Sydney Basins in Australia for example, the seam gas can range from pure methane to pure carbon dioxide. Carbon dioxide is found in the seam gas in France, Poland and Czechoslovakia.

The interaction between coal and gas is not straight forward, as the gas can exist in three states within the coal. The majority of the gas within the coal occurs as an adsorbed, liquid-like, mono-molecular layer on the walls of the micropore system. Gas also exists in the

free state, both in macro and micropores, and to a lesser extent it exists in solution in any water present.

Outbursts involving carbon dioxide tend to be more violent than those involving methane. The sorptive capacity of coal for carbon dioxide is two or three times greater than for methane, although from the molecular size the reverse would be expected. In addition, the desorption of carbon dioxide is much faster than methane, which implies that the pressure gradients are higher when carbon dioxide is present, which would explain the greater violence of carbon dioxide outbursts. It has been suggested that under the influence of excess stress the methane/coal system is in a metastable state.

The mining operations stimulate the change of methane into a gas phase, (a 'gas collapse'), as opposed to a two component interstitial solid solution. The resulting increase in gas pressure triggers the outbursts, although observations of the progressive development of a particular type of microseismic activity prior to outbursts tends to cast doubt on this model.

Outbursts are usually associated with major or minor structural and sedimentological features, which create excess stress and strain within the coal seam. These features may occur, on a large scale, in the case of faults or folds or at a smaller scale, roof rolls for example, or even as microscopic irregularities in the coal micro-structure. They are also often associated with sedimentary features, such as palaeo-fluviatile channels within the coal seam, or with the presence of a thick competent sandstone roof, although it is the stress-containment aspect in this case which is critical to outburst occurrence.

2.2 Outbursts in the Sydney Coalfield

The major underground coal mines in Canada are located in Cape Breton Island, Nova Scotia, Figure 1, the majority of the mines of Alberta and British Columbia having closed in the early 1960's, with some operating through into the 1980's and some still operational. The mines are owned and operated by the Cape Breton Development Corporation. The productive measures of the Sydney Coalfield lie within a 2200m sequence of strata known as the Pictou Group. The coal is classified as high volatile "A" bituminous coal. The strata between coal seams are sandstones, siltstones, mudstones, with minor shales and non-marine limestones, and these are interpreted to be of a fluvial origin.

Between 1977 and April 1984 the No. 26 Colliery, being the deepest mine in the Sydney Coalfield at the time, experienced 37 rock-gas outbursts. The results of a review of the rock-gas outburst events (CANMET, 1987) that have occurred in the Sydney Coalfield indicate that the majority of them occurred in development headings driven in virgin coal, initiated by blasting and occurred whenever a sandstone erosion channel was present within 2.7m of the top of the coal seam. Sandstone channels are observed within the seams or in close proximity. Mapping of the sandstone channels, (Forgeron et. al., 1986), has shown that they are linear in nature and move down from, or up into the roof strata in an unpredictable manner. Their coarse grained texture suggests that they represent in-filled palaeo-river channels which eroded and migrated across the alluvial plain replacing the normal roof sequence and in some cases the coal itself.

Some of the observed effects of the sandstone channels that are of importance are:-

i) that the roof adjacent to the sandstone "pinch-out" zone tends to be weak.

ii) the sandstone-mudstone contracts constitute planes of weakness along which rock immediately separates.

iii) the channels reduce or destroy the natural beaming strength of the roof strata.

iv) outbursts generally originate from such sandstone above the seam. Five of these sandstone channels were identified in No. 26 Colliery and outbursts were recorded to be associated with each.

v) the sandstone channels are limited in width and their geometrical shape makes it difficult to delineate them in three dimensions using borehole data. Other techniques could be considered to define their shapes.

There is no major faulting within the coalfield and the major structural features are the gentle northeast trending folds that plunge north east at four to ten degrees, forming the Sydney Synclinorium. No major tectonic activity has perturbed the area, unlike the South Wales Coalfield for example.

In-situ stress measurements have been carried out at four sites in the Sydney Coalfield, including the Donkin Mine, No. 26 Colliery, Prince Mine and Lingan Mine. In each test program the stresses measured have been resolved in components in N-S, E-W and vertical directions and the stress tensors were evaluated for No. 26 Colliery and the

Prince and Lingan Mines by a method of least squares. The in-situ stress data is an important parameter for the study of the rock and gas outburst problem. In general it was seen that the major principal stress trends E-W and the intermediate principal stress is orientated in the N-S direction. Both these principal stresses are close to or slightly off horizontal. The minor principal stress is close to or slightly off vertical. It is seen that the general trend is a gradual increase in stress with depth. The vertical stress components measured at the four sites are generally consistent with the overburden stress.

The horizontal stress components at Donkin Mine, No. 26 Colliery and Prince Mine differ only slightly, suggesting a fairly isotropic horizontal stress regime. At the Lingan Mine the major E-W principal stress is significantly higher than the intermediate principal stress. It is considered that this may have resulted from the influence of the monocline which trends E-W across the mine.

There was no correlation between the direction of the drivage and the occurrence of outbursts, although it is considered, on a world wide basis, that cross measures working are more outburst prone. The majority of these outbursts were initiated by blasting (shot firing) and all but three occurred in development headings. The remaining three caused minimal damage, with no noticeable outburst cavity. All of these outbursts occurred between 703m and 790m below sea level. The frequency and intensity of the outbursts increased with depth, as would be expected. At first, damage to the development heading was insignificant, but as the working depth increased so did the resulting damage. The failure surfaces exposed within the outburst cavities were typical of surfaces resulting from shear failure. The bursting formations were

invariably sandstones, sometimes with interbedded siltstones.

Prior to June 1983, if there was gas associated with these outbursts it was neither detected, tested nor recorded. However, in latter events substantial quantities of methane gas was detected after each outburst.

The last two outburst events (36 and 37) in the No. 26 Colliery, of November 1983 and June 1984, resulted in the destruction of 18m of roadway and the release of considerable quantities of methane into the workings. The methane content in the return airway in No. 26 Colliery was estimated at the time of outbursts 36 and 37. The volume of rock ejected during these two events was also determined following the events.

The estimated volumes of gas and rock ejected were :-

Outburst Event No.	Volume of Gas Estimated (m^3)	Volume of Rock Ejected (m^3)
36	753	316
37	3171	145

The association of a large volume of gas with the later outbursts was the main cause for concern. The gas envolved contained 75 - 80 % Methane, 10% Nitrogen, and 5 - 10% Ethane, with the balance comprising higher hydrocarbons and carbon dioxide. The violence of the latter outburst events could quite easily have caused an explosion of the methane/air mixture present in the mine, with catastrophic results.

Based on a discussion with officials of the Nova Scotia Department of Mines and Energy, gas pressure measurements made during offshore drilling ventures in the vicinity of

the Sydney Coalfield, to a depth of 4500m, indicate an increase in gas pressure of 10.74 kPa per metre depth. At a depth of 790m would indicate a gas pressure of 8.5 MPa.

It was considered that workings in the other operating mines in the Sydney Coalfield, for example, the Lingan and Phalen Mines could encounter similar conditions as mining reached greater depths.

2.2.1 Outburst Initiation Mechanism for the Sydney Coalfield

Based upon a review of the data collected and similar outburst phenomena reported elsewhere, an initiation mechanism was proposed for the rock-gas outbursts of the Sydney Coalfield (CANMET, 1987).

It is suggested that the creation of an opening by shotfiring results in the creation of a biaxial stress field at the opening boundary which would induce tensile cracking across the bedding planes. Further into the rock mass the stress field becomes triaxial and the mode of failure is generally dominated by shear failure.

The dynamic stresses from shotfiring superimpose additional transient compressive and tensile stresses on the rock mass. This would induce further tensile stresses on the rock mass, which would in turn enhance the development of fractures in close proximity to the surface of the opening. Further fracturing may be induced by dynamic recovery after the sudden release of confinement. It is further suggested that any gas trapped in the sandstone would respond to the changes in stress. The pore gas pressure increases, and the permeability decreases, as the induced stress increases. At the boundary of the opening high biaxial stresses tend to

induce fractures which generally closely follow the trajectory of the major principal stress.

The pore gas escapes into these fractures and, still under pressure, contributes to the propagation of the fractures. If the gas pressure is sufficient to overcome the confining stresses the fractures will continue to propagate and eventually break into the free face. The kinetic energy of the escaping gas is dissipated as the broken rock fragments are ejected from the cavity. The creation of a new face and the redistribution of stresses around the opening results in further fracturing and the process repeats itself, accelerating to failure.

In general it would appear that the events experienced within the Sydney Coalfields are not classical coal outbursts but appear to be more akin to the "roof bursts" of France. These are characterized by a violent failure of the roof with a sudden relief of elastic energy near the workings. The dynamic loading is then fully transmitted to the coal seam which is then ejected.

3. AN OVERVIEW OF MICROSEISMIC MONITORING IN MINING

Miners have traditionally reported hearing rock noises or 'pounces' prior to outbursts. These have been described as the sound of a 'two-stroke motorbike engine' or of 'tearing brattice cloth'. The 'pounces' are the audible expression of acoustic emission/microseismic activity (AE/MS) occurring as failure of the seam proceeds through the states of deformation from movements at the atomic level (dislocations at grain boundaries) to large scale fracturing of the body of rock. The frequency of the emitted seismic signals range from less than 1Hz (infrasonic), with the characteristic frequency of the events, the corner frequency, (Brune 1970), being dependent upon the scale of the failure occurring at the rupture surface within the rock matrix.

The possibilities offered by AE/MS monitoring were apparent from an early date. Knill, Franklin and Malone (1968) have summarised the application of acoustic techniques in this field of research. The earliest investigations were directed mainly towards the prediction and location of rockbursts and similar catastrophic deformation processes (presumably outbursts) in underground excavations.

3.1 The Methodology of Microseismic Monitoring

The dangers of outbursts are summarised by a number of authors including Kozlowski (1983), Roberts (1983) and Davies (1980) as:-

- the displacement of a mass of coal into the workings, burying personnel and possibly clogging ventilation systems.

- the possibility of suffocation by dust or in an oxygen deficient atmosphere, or the possibility of poisoning by toxic gases.

- explosions of flammable gases, chiefly methane, caused by damage to electrical equipment or sparks of a mechanical nature.

- secondary caving.

- transport of machinery over large distances.

- suffocation of people and animals on the surface of the mine by large quantities of gas passing up ventilation shafts.

Apart from the obvious hazards to personnel, the mine will suffer economic losses; production will invariably be disrupted for days or even weeks. In severe cases they result in the mine being closed.

The development of a microseismic system should therefore assist in the identification of outburst prone areas and for the prediction of outbursts. The importance, however, of not relying on one system, but combining approaches should always be considered and cannot be over emphasised, a combined approach being reported for the case of Cynheidre, S.W. Wales, is cited (Styles et. al., 1990). Apart from the tangible products of identifying outburst prone areas, highlighting the risk of outburst and its effect on the safety of personnel, systems should also ultimately assist in the prediction of outbursts and they should in themselves help in the reduction of psychological stress of personnel working in outburst prone areas. A system capable of providing warnings should be capable of being used as a management 'tool' to control mining so that outbursts do not occur in an

uncontrolled fashion and consequently reduce the length of time lost due to the uncontrolled occurrence of outbursts.

Outbursts are generally preceded by a stress redistribution in the coal and adjacent strata involving fracturing of both coal and rock (Roberts, 1983). It has been demonstrated that under compression fracture processes consist of three distinct stages:-

- crack initiation
- crack propagation
- ultimate fracture

It is the coalescence of numerous cracks rather than the propagation of a single crack that leads to ultimate failure. Each stage of crack development generates pulses of seismic energy, the magnitude of which is proportional to the size of the crack and the amount of displacement (Jackson, 1984). It is this seismic energy generated which is monitored by microseismic monitoring systems.

In its most simple form a passive microseismic monitoring system requires a transducer, or an array of transducers, a transmission system and a method of discriminating between noise, microseismic activity and teleseismic, regional earthquakes. As such a system is composed of three distinct elements which can range in complexity depending upon the application of the system.

The transducers of the system developed is a simple choice effectively between two main types, but the choice of the specific units used is of fundamental importance to the effectiveness of any system. The simple choice being between geophones or accelerometers, either as single units or triaxial sets. This choice is effectively dependent upon the expected frequency range of the seismic signals to be monitored.

The transmission system can be simple, from analogue transmission along cable pairs, or coaxial cable, or through an extensive range of signal conditioning units, including pre-and post amplifiers, filters, and can be complex with the use of multiplexers and digital transmission via fibre-optic cables and radio telemetry.

The third component of the system can range from a simple loud speaker, through oscilloscopes, chart recorders, tape recorders, through to multi-tasking priority based on-line computer systems. It must, however, be emphasised that to obtain an understanding of the nature of the phenomenon it is necessary to record full waveform data for subsequent analysis, and some complexity should be built into this component of any system.

As it has been mentioned the transducers used in any system are selected based upon the anticipated frequency content of the signals to be monitored. The anticipated frequencies have resulted in a two fold nomenclature for such systems. For frequencies less than 100Hz, events are commonly referred to as microseismic (MS), while events having frequencies above this 'threshold' frequency are commonly referred to as acoustic emissions (AE), although no objective scientific rationale exists for this division. This in turn leads to systems being referred to as microseismic systems or alternatively acoustic emission monitoring systems.

Microseismic or acoustic emission monitoring of mines can be carried out from three deployment positions:-

i) Underground Monitoring
ii) Surface systems (including shallow boreholes)
iii) Borehole systems (at seam level)

The techniques have been applied to many mining situations, as failures in all four failure categories outlined in Section 2 result in the generation of microseismic activity. Consequently systems of varying complexity from simple portable hand held systems through to complete digital systems with on-line computer processing capabilities have been developed. Most of the systems which have been reviewed have been developed and deployed as research tools and have either been constructed by the research group or assembled on an ad hoc basis to fit the requirements. Systems reviewed include those for predicting roof falls, outbursts and rockbursts. A detailed review of previous development and operation of microseismic networks in different countries is presented under their appropriate deployment headings on a country by country basis in Appendix A. An overview of the technical details and their relevance to the Sydney Coalfield is presented here under the headings:-

- coal mining applications
- hard rock including mineral applications
- evaporite mining applications
- systems of relevance to the Sydney Coalfield

Other techniques are occasionally used in conjunction with microseismic monitoring techniques, such as numerical modelling to predict stress concentrations and also seismic tomographic imaging. This latter technique is briefly reviewed in Section 3.6.

3.2 Overview of System Developed for Coal Mining Applications

Microseismic monitoring systems and acoustic emission systems have been identified and reviewed from the USA, the UK, Germany, France, Australia, Japan, China, the USSR, Czechoslovakia, Poland and Hungary; these are

summerised in the following tables and briefly discussed.

The occurrence of outbursts in the USA is relatively limited, partly due to the fact that most active mines are relatively shallow and do not suffer from high stress conditions. Consequently relatively few microseismic studies for outburst prediction have been conducted in the USA. However, it is anticipated that as mining occurs at greater depths and in more complex deposits, the incidence of outbursts will increase.

Location	System Type
Western Colorado, U.S.A Leighton and Steblay, (1975) Leighton (1984a; 1984b; 1985)	Geophones 15 - 250Hz ultrasonic transducers 36-44kHz developed as the McPhar Rock Monitor
Pennsylvania, U.S.A. Hardy and Mowrey (1976) Mowrey and Hardy (1978)	15 channels, 14Hz Geospace geophones, FM seven channel tape recorder
Paradox Basin, Utah, U.S.A. Eastern Wasatch Plateau, Utah, U.S.A. Wong (1984), (1985), Wong et. al., (1989); Wong and McGarr (in press)	24 channels, 1Hz seismometers 9 station 3D high resolution, digital and analogue network

Leighton and Steblay (1975) describe research carried out by the U.S.B.M. in deep coal mines of Western Colorado, using two frequency bands. A lower frequency band using geophones with a bandwidth of 15 to 250Hz and monitoring in the 36-44kHz band. Continuing research is described by Leighton (1984a; 1984b), in the 40 to 110kHz range, to monitor activity prior to and associated with outbursts. The system is only effective over short distances and is insensitive to man-made noise. Reasonable results were obtained using the energy/event ratios, with precursors demonstrated some 15 minutes preceding outbursts. A commercial development of this is the McPhar Rock Monitor reported by Leighton (1985), an assessment of which has been carried out by Ersavci (1989). It was considered,

after initial problems, that there was potential for its use for the detection of roof falls.

Hardy et. al., (1987a) reports the testing of such a high frequency system in a number of coal mines with an early warning for 20 out of 23 ground failures and it is reported that the system has met with considerable success in coal mines and Canadian Potash Mines.

The above systems have been deployed underground, some, however, have been deployed on the surface. Such a system is described by Mowrey and Hardy (1978) in which an array of 15 geophones were deployed in shallow boreholes, to monitor activity associated with longwall coal mining. Similar systems were reported to be operating during the period 1970-77 in longwall coal mining studies (Hardy, 1980, 1982).

Wong (1984) and Wong (1985) describes the use of a 16-24 channel microseismic network, using short period seismometers, to monitor seismicity associated with coal mining beneath Book Cliffs, and subsequently monitored by a 9-station digital network. Wong et. al., (in press) also reports monitoring of coal mines of the Eastern Wasatch Plateau, Utah, using a three dimensional network of analogue and digital seismographs operated in the vicinity of two coal mines beneath Gentry Mountain.

In the United Kingdom, outbursts have represented a serious problem in the anthracite zone of the South Wales Coalfield. Cynheidre Colliery, was the last operating mine to which outbursts have been attributed, as other outburst prone mines of Yorkshire, Lancashire, North Staffordshire, Scotland and Wales have been closed.

Location	System Type
North Staffordshire, U.K. Westbrook et. al., (1980); Kuznir and Farmer (1983); Kuznir et. al., (1980), (1982) and (1984)	12 channels, Willmore MK III seismometers, geostone recorder
Cynheidre Colliery, S. Wales, U.K. Brown and McDonald (1984); Rigby and Wardle (1984); Rigby and Bolt (1989)	4 channel, geophones grouted in seam, with FM telemetry to surface on-line detection and processing HP9816 computer
Cynheidre Colliery, S. Wales, U.K. Styles et. al., (1987a), (1987b), (1988) and (1990)	8 channel digitial, Willmore MK III seismometers automatic on-line microprocessor system

Initial monitoring at Cynheidre, the site of 114 serious outbursts was performed using an accelerometer and a portable tape recorder which recorded in-seam activity and frequent 'pouncing' events prior to a spontaneous outburst (Hughes, 1973).

An underground monitoring system developed by the University College of Cardiff (Brown and McDonald, 1984; Rigby and Wardle, 1984; Rigby and Bolt, 1989), consisted of four geophones grouted in boreholes in-seam with FM telemetry to the surface. The system recorded seismic events which showed a correlation with methane emission from the face, unfortunately no outbursts occurred during the period of full-time deployment, consequently further conclusions cannot be drawn.

A surface system was also deployed to monitor Cynheidre Colliery and seismicity associated with outbursts. The system, developed at the University College of Swansea (Styles et. al., 1987a; 1987b) used an eight channel network of seismometers, with data telemetered by FM digital radio links. The data was recorded on a digital cartridge recorder and processed in real time by an on-line micro-processor which issued warnings based on event rates. It was possible to detect, identify and locate

microseismic activity associated with normal mining activity and a new type of seismic activity associated with microfracturing of the coal and the emission of methane during periods of abnormal face conditions. This surface network monitored precursory activity to outbursts and was used as a predictive tool issuing warnings at times of potential outburst risk, to aid management in the safe working of the colliery. It is considered that this technique combined with specialised destressing techniques resulted in the mine being worked for more than four years without an outburst occurring.

Similar systems have been used to monitor mining induced seismicity associated with coal extraction in the North Staffordshire coalfield, these used standard seismological seismometers deployed on the surface, Westbrook et. al., (1980); Kuznir et. al., (1980, 1982, 1984), and Kuznir and Farmer (1983).

In West Germany a considerable amount of research has been undertaken.

Location	System Type
Radbod Mine, Westfalen Mine, Ruhr, West Germany. Will (1980), (1984a), (1984b), (1984c), (1989). Will et. al., (1985)	Permanent 12 channel and portable intrinsically safe sysems. 32 channel, digital PCM MESAS system. Full waveform acquisition and processing
Ruhr, West Germany. Hahnekamp (1984); Steinwachs (1984)	4 channel system

Permanent 12-channel underground systems (Will, 1980) and portable instruments have been developed jointly by WBK (Bochum) and Lennartz for monitoring seam reactions during destressing drilling in outburst prone areas (Will, 1984a, 1984b).

A system designed for use during longwall retreat operations (Will et. al., 1985), consisted of 16 channels, each with a bandwidth of 1000Hz. A total of 32 geophones were used with signals transmitted to an underground monitoring station, where 16 are selected for transmission to the surface as a PCM coded signal. This has been developed by WBK and Lennartz (Will, 1989) as the MESAS, a fully digital PCM underground system, which applies specialised software, that takes account of the dispersive nature of the events, which does not appear to feature in other systems.

A number of other studies have been conducted using transducers installed in coal seams, mostly initiated to study the effects of mining and the efficiency of destressing techniques on seam stability, these are described by Baule and Rao (1979) and Will (1980, 1984a, 1984b).

Surface transducers have also been deployed to detect and locate sources of activity in a number of coal mines in the Ruhr, Baule (1977); Casten and Cete (1980) and Will (1984b). Four channel systems with telemetry systems for use in remote areas have also been developed (Hahnekamp (1984); Steinwachs, (1984)).

In the Provence coalfield of France the relationship between face advance and energy released per shift has been established with the operation of a 4 channel system, Dechellette et. al., (1984); and Revalor et. al., (1986). They have attempted to identify the onset of outburst conditions using departures from this relationship, the investigations indicated that suitable criteria existed for the classification of zones approaching a dangerous condition.

Location	System Type
Provence, France. Dechellette et. al., (1984) and Revalor et. al., (1986)	4 channel underground system
Provence, France. Revalor et. al., (in press)	4-7 geophones underground 10-300Hz. 8-12 single and triaxial geophones up to 30Hz surface and underground, full waveform data recorded

Revalor et. al., (in press) described the application of two systems to the monitoring of seismic activity related to what they describe as 'coal bumps', which appear to be either bumps or coal bursts. The first is a panel based system deployed to monitor one longwall face, using between 4 and 7 geophones, located in either the roof or floor. Whilst the second is, a larger network used to locate seismic events and to study focal mechanisms. This uses between 8 and 12 geophones, both single axis and triaxial, located both on the surface and underground.

Location	System Type
West Cliff Colliery, New South Wales, Australia. McKavanagh and Enever (1980)	Single channel system recorded single in the 100Hz to 5kHz range accelerometers in the coal rib
Leichardt and Metropolitan Colliers, B.H.P. Grezl et. al., (1984)	Detected in-seam channel waves and enhanced activity 17 days before an outburst

In Australia McKavanagh and Enever (1980) developed a single channel system monitoring AE/MS system which recorded signals in the 100 to 5kHz range prior to outbursts in the West Cliff Colliery, N.S.W. and a reduction in the rate of activity was noted 10 minutes prior to outbursts, and warning times of 0-17 minutes were claimed to be attainable. Further development was aimed at producing an intrinsically safe audio/visual warning system for mounting on a continuous miner.

Grezl et. al., (1984) built on this work and deployed underground systems to predict outbursts at the Broken Hill Proprietry Company Ltd., (BHP) at both Leichardt and Metropolitan collieries with accelerometers deployed in the coal rib. Enhanced background seismicity occurred for 17 days prior to a 25 tonne outburst, with a reported reduction in activity several shifts before the outburst.

Location	System Type
Akabari and Ohyabari, Hokkaido, Japan. Nakajami et. al., (1984)	2 channel system
Sunagawa Coal Mine, Japan. Isobe (1974), Isobe et. al., (1976), (1977), (1979), (1980) and (1984); Sato and Fujii (1987)	Mine wide seismic network, 8 geophones installed underground and on the surface
Horonai Mine, Japan. Sato et. al., (1989)	Underground array of accelerometers or geophones 10 channels, with 6-8 on the surface
Akabira, Sunagawa, Horonai Mines, Japan Watanabe et. al., (1984)	2 channels, accelerometers pre-amplified, Dunegan/Endevco and Marubun equipment, tape recorder and spectrum analyzer
Mike Mine, Japan. Kaneko et. al., (in-press)	12 channel underground system of seismometers

Outbursts have been a major problem in Japan, with an explosion occurring at the Ohyubari Mine, Hokkaido in 1981. The disaster occurred in a gate road heading believed to have been made safe by stress relief drilling and gas drainage (Hirota et. al., 1983). A two channel system was installed to monitor activity during advance boring for methane drainage (Nakajima et. al., 1984).

Isobe (1974) and Isobe et. al., (1976, 1977, 1979, 1980, 1984) report a combined surface and underground system used at the Sunagawa Coal Mine where three rockbursts occurred in 1968. An outburst occurred in a cross cut just after blasting with anomalous microseismic activity monitored by a mine wide seismic array consisting of eight

geophones installed both underground and on the surface (Sato and Fujii, 1987).

Monitoring at the Horonai Mine has been conducted since 1980, using an underground array of accelerometers or geophones, or by using a near surface array of geophones, (Sato et. al., 1989). Underground seismic signals were digitised before transmission and any signals that exceeded a preset level were recorded automatically using a triggering method.

Acoustic Emission studies have been conducted at the Sunagawa mine since 1976, Horonai mine since 1978 and Akabira mine since 1979, using Dunegan/Enderco and Marubun equipment (Watanabe et. al., 1984). The system consisted of two transducers, pre-amplifiers, a tape recorder and a real time spectrum analyzer when necessary, with signals being transmitted to the surface.

At the Miike Coal Mine, an undersea mine, pure coal bursts have occurred with no associated gas. A 12 channel source location system, using seismometers deployed in roadways was installed (Kaneko et. al., (in press)).

Location	System Type
Mentouge Mine China. Li (1989)	Single channel portable systems
First Coal Mine, China. Zhang et. al., (1987)	Accelerometers deployed in boreholes, monitored by a Dunegan/Endevco 300AE monitor

In China, Li (1989) described the design of two portable, single-channel AE monitoring facilities, which have been used to predict coal bursts. The results showed some increase in AE rates prior to some failures, but other failures occurred without any apparent warning. However, an anomalous increase in emitted energy was reported some

two days prior to a coal burst at the Mentouga Mine.

A joint study of the relationship between acoustic emission and gas emission during drilling was carried out co-operatively between the Fushun Coal Research Institute and Hokkaido University at Yangquan First Coal Mine using accelerometers deployed in boreholes with monitoring being conducted on a Dunegan/Endevco 300 AE monitor (Zhang et. al., 1987).

Location	System Type
U.S.S.R. Antsyferov (1966)	More than 150 faces monitored in 37 collieries
Czechoslovakia. Simane 1963; Stas et. al., (1971); Roček et. al., (1975); Dlouhy (1976)	Reports of microseismic monitoring and automated monitoring systems
Doubrava colliery Ostravia-Karvina Coal Basin Czechoslovakia. Holub (1985); Holub et. al., (1987)	3 channel, digital, intrinsically safe system, developed with surface and underground data
Klando coal mines, Czechoslovakia Rudajev et. al., (1985)	6 channel, 2 underground 4 on surface
Poland. Gibowicz (in-press)	30 underground networks
Poland. Trombik and Zuberek (1977), (1980)	Multi-channel system and portable single channel, development of a semi-automatic system. Source location studies using geophones ahead of the face recorded on a multi-channel tape recorder
Hungary. Sombati (1983)	Acoustic tomography and preliminary microseismic studies
Hungary. Peter and Pellioniaz (1980) Peter et. al., (1981)	32 channels monitoring capability and computer processing, monitors in the 50Hz to 2kHz range

In the early 1950's in the USSR 'listening apparatus' similar to that designed by Obert (1941), was used in an attempt to forecast outbursts which met with limited success and was further developed. It is reported that

more than 150 faces have been monitored at 37 collieries with some promising results (Antsyferov, 1966).

During the 1960's microseismic monitoring was conducted in Czechoslovakia (Simane 1963), and Stas et. al., (1971) reports that research has been active for some years. More recently Dlouhy (1976) and Roček et. al., (1975) discussed the development of an automated microseismic monitoring facility and its application to rockburst problems in bituminous coal mines. Little information has, however, been published in recent years, although it is suggested that mine wide systems are in use at some coal mines. Holub (1985) and Holub et. al., (1987), report microseismic investigation from the Doubrava Colliery in the Ostrava-Karvina Coal Basin, where a digital, 3-channel system was developed and deployed with surface and underground data monitored and analysed. A six station network has been developed at the Klando Coal Mines, with two stations underground and the remaining 4 on the surface (Rudajev et. al., 1985).

Microseismic research in Poland through the late 1970's has been extensive (Hardy, 1987a) using both in-mine and surface transducers with results used for scheduling destressing programmes and warning of possible rockbursts and outbursts.

Extensive work is currently taking place (Gibowicz, 1984), where it is reported that there are a total of 30 underground microseismic networks (Gibowicz, (in press)), however, little information is available as to the equipment specifications. Both stationary multi-channel systems and portable single-sensor apparatus have been developed (Trombik and Zuberek, 1977), with later development of a semi-automated system. Trombik and Zuberek (1980) also report a series of source location studies, to evaluate the effects and efficiency of

destressing blasting. These studies carried were out using geophones, installed both ahead of the longwall faces and in worked areas. The data, in the frequency range of 20-1200Hz was recorded on a multi-channel tape recorder.

During the 1980's, the Hungarian Central Research Institute for Physics developed a wide range of microseismic monitoring equipment (Peter and Pellionisz, 1980 and Peter et. al., 1981). Including a mobile 32 channel monitoring capability and associated computer facilities for data processing and storage in the frequency range 50Hz to 2kHz. Simple acoustic tomography and preliminary microseismic studies have also been reported from a number of coal mines (Sombati, 1983).

3.3 An Overview of Systems Developed for Hard Rock Applications

Microseismic monitoring systems and acoustic emission systems have been identified and reviewed from Canada, the USA, Sweden, Australia and India; which have been summarised in the following tables, with additional information briefly discussed.

In Canada the interest in microseismic monitoring stems mainly from the rockburst problems in hard rock mines, particularly in Ontario and Quebec. As of 1985, 10 multi-channel monitoring systems with varying degrees of sophistication, with 8-64 transducers, were either installed or in the process of installation in Canadian Mines (Udd and Hedley, 1985). As of 1987, this figure had increased to 14 systems in Ontario alone (Hedley, (in press)). All of which are based on the Electro-Lab 250MP with a maximum of 64 channels. The systems are operated for real time source location of events and to provide an indication of magnitude (Hanson et. al., 1987).

Under the Canada-Ontario-Industry Rockburst Project, seismograph units were to be installed at Red Lake, Elliot Lake, Sudbury and Kirkland Lake to obtain records of larger seismic events and their magnitude (Hedley and Udd, 1987). Microseismic systems consisting of triaxial strong-motion geophones, including processing units for event detection and data digitisation were also to be installed around Campbell Red Lake, Quirke, Strathcona, Creighton and Macassa mines. The capture of complete waveforms would allow for the investigation of the source mechanisms of the rockbursts.

Location	System Type
Strathcona Mine, Sudbury, Ontario Hedley and Udd (1987)	32 accelerometers Electro-Lab 250MP 5 Teledyne-Geotech Strong Motion Accelerometers, analogue Cable Telemetry. Triaxial Strong Motion Geophones on surface, full waveform capture
Strathcona Mine, Sudbury, Ontario. Davidge (1987); Young et. al., (1987a)	Full waveform acquisition and processing triaxial sets
Strathcona Mine, Sudbury, Ontario. Talebi et. al., (in press)	R.C. Electronics, P.C. based system and Electro-Lab 250MP. 5 Triaxial sets, could take 32 channels
Lockerby, Ontario Hedley and Udd (1987)	32 accelerometers Electro-Lab 250MP
Fraser, Ontario Hedley and Udd (1987)	16 accelerometers Electro-Lab 250MP
Falconbridge, Ontario Hedley and Udd (1987)	Originally 8 accelerometers Electro-Lab 250MP
Onaping, Ontario Hedley and Udd (1987)	16 accelerometers Electro-Lab 250MP
Campbell Red Lake, Ontario Neumann and Nakuch (1989) Hedley and Udd (1987)	64 Channel accelerometers Electro-Lab 250MP Triaxial strong motion geophones on surface, full waveform capture

Creighton Mine, Ontario Oliver and McDonald (1989) Hedley and Udd (1987)	48 channel, accelerometers Electro-Lab 250MP Triaxial strong motion geophones on surface, full waveform capture
Macassa Mine Hedley and Udd (1987) Quesnel and Hong (1987)	12 channel, 8 connected to Gould waveform recorder, Eventually 38 channel with 5 triaxial strong motion geophone sets on surface with full waveform capture
No. 12, Bathurst New Brunswick Kristof et. al., (1987)	32 accelerometers frequency 80Hz to 8kHz Electro-Lab 250MP full form capture
Denison Mine, Elliot Lake, Ontario Calder et. al., (in press) Yeo (1987) Hedley (in press)	Portable high frequency system piezo-electric accelerometers 50-400kHz, processed by a priority based multi-taking programme. Micro-processor based acquisition system Triaxial geophones, 2-250Hz underground and 5 geophone sets on the surface, 8-300Hz
Quirke Mine, Ontario Hedley (in press) Semadeni et. al., (in press)	Triaxial geophones, 2-250Hz underground and 5 geophone sets on the surface, 8-300Hz 5 Geospace 8Hz geophones in shallow boreholes FM modulated, multiplexed and transmitted by fibre optic links, full waveform recording vertical axes connected to Electro-Lab 250MP.
New Quirke Mine, Ontario MacDonald (1982)	16 accelerometers Electro-Lab 250MP
Copper Cliff North Mines, Ontario Hedley and Udd (1987) McDonald and Cockhrane (1987) Yeo (1987)	Electro-Lab 250MP Micro-processor based acquisition system
Garson Mine, Ontario Hedley and Udd (1987) MacDonald and Cochrane (1987)	Electro-Lab 250MP
East Malartic Mine, Northwestern Quebec. Bourbonnais (1984)	10Hz geophones, pre-amplified transmitted by cable to an RBM.
Elliot Lake, Ontario. Labuc and Mosch (1987)	5 Triaxial geophones at the surface bandwidth 0.5-300Hz fibre-optic links Masscomp DN5400 work station. Underground system, broadband accelerometers, Electro-Lab 250MP
Sudbury Basin mines of INCO Ltd and Falconbridge Ltd Plouffe et. al., (in press)	3 digital short period Teledyne-Geotech S13 seismometers, frequency range 1-16Hz. PDP 11/73 and Microvax II computers

At the Strathcona Mine in addition to the Electro-Lab system five Teledyne-Geotech strong motion accelerometers installed underground and on the surface (Hedley and Udd, 1987), with the analogue signals telemetered by cable. Real time processing hardware performs event recognition and digitisation at the mine and further waveform analysis in performed at the Elliot Lake Laboratory of CANMET. Complete analysis involves both traditional and modified procedures, including pattern recognition to classify the source.

A combined system using geotomography (Young et. al., 1987a) and the collection of full waveform data is also used Davidge (1987). Along with a two PC based system (Talebi et. al., (in press)) which uses five clusters of triaxial accelerometers and 16 single component geophones of the existing automatic multi-channel monitoring system, an Electro-Lab 250MP. The system records full waveform data, recorded using a trigger logic unit.

A temporary 12 channel network was installed at Macassa Mine, eight of which were connected to a Gould waveform recorder (Hedley and Udd, 1987). The goal was to install a 48 channel system for source location (Quesnel and Hong, 1987). To enable first motion studies, 5 triaxial geophones are to be installed with a Gould waveform analyser.

At the No. 12 mine, Bathurst, New Brunswick the Electro-Lab 250MP system (Kristof et. al., 1987), was augmented by a full waveform capture system which would allow for frequency domain analysis and digital filtering.

A portable high frequency data acquisition system was operated at the Denison Mine near Elliot Lake using a piezo-electric accelerometer (Calder et. al., (in press)). The signals were conditioned before being processed by a

computer, controlled by a priority based multi-tasking programme. Precursor analysis was based on feature extraction techniques and pattern recognition, which did not, however, reveal any precursory behaviour prior to a rockburst.

A computer based system constructed around a COMPUTERSCOPE - IND digitising board has also been used at the Denison Mine, as well as the Copper Cliffe, North Mine, Ontario (Yeo, 1987). The board allows the computer to act as a digital oscilloscope and for the setting of triggering conditions. The system ran on a Zenith microcomputer and was later transferred to run on a Compaq portable II.

At both Denison and Quirke mines, triaxial geophones have been installed underground augmented by five geophone sets on the surface (Hedley, in press).

The Quirke mine is also monitored by a surface microseismic network developed by Noranda under a CANMET contract. The system uses geophones, deployed in shallow boreholes, (Semadeni et. al., (in press)), with the signals frequency modulated, multiplexed and transmitted by fibre optic links. Events are considered valid and saved when the signals exceed a pre-set trigger threshold from sufficient sites. The vertical axes of the sensors are connected to the 250MP which also calculates source locations. Spectral analysis of the signals is also performed.

Bourbonnais (1984) describes a microseismic system operating in the East Malartic Mine, in Northwestern Quebec to monitor activity associated with rockbursts, using 10Hz geophones mounted in boreholes. The signals were pre-amplified prior to being transmitted by cable to the monitoring facility which consisted of a filter interface; a threshold detector; and a RBM digitial

microprocessor. Source location was accomplished using three techniques; the Generated Block Method, the p-wave Direct Solution and the p-wave Least Squares Method.

A macroseismic system was developed by Noranda and deployed as a research tool at Elliot Lake in 1987, which consisted of 5 triaxial sensors deployed in an approximately $1km^2$ array to monitor a section of the mine. The transducers, initially servo-accelerometers were replaced by geophones, with signals were telemetered by fibre optic links (Labuc and Momoh, 1987). Data acquisition and analysis is performed by a Masscomp DN5400, with acquisition software running at a high priority to ensure 24 hour operation. An event was recognised by a 4 point moving average exceeding a pre-set trigger.

Within the Sudbury area a digital seismic network has been established using standard Teledyne-Geotech seismometers, linked to the Science North processing centre by dedicated telephone lines, where data is recorded on drum recorders. The STA/LTA trigger algorithm is used to save any events on a PDP 11/73 computer (Hedley and Udd, 1987). Data is also transferred to Ottawa where data analysis is performed, including source location and the calculation of source parameters.

In the USA the first documented rockburst is believed to have occurred in 1904, in the Atlantic Mine, in the Copper district of Michigan. A severe rockburst finally caused closure of the mine in 1906. At the present time, the only area where this is a problem, is the Coeur d' Alene metal mining district of northern Idaho.

Location	System Type
Galena Mine, Coeur d' Alene Idaho Bolstad (in press)	32 channel stope orientated system, fibre optic links, single short period seismometer on surface
Coeur d' Alene, Idaho Brady (1987)	Triaxial geophones and associated electronics for analogue recording. Teledyne-Geotech helicorder.
Galena Mine, Coeur d' Alene Idaho Blake and Leighton, (1970) Leighton and Blake, (1970)	High frequency, accelerometers cemented in boreholes underground, 7 track analogue tape recorder
Star Mine, Idaho Langstaff (1977); Blake (1984a)	24 channel micro-processor based
White Pine Copper Mine, Michigan. Gibbons (1980)	2 Mark L-1B geophones, pre-amplifier, Gould 222 strip chart recorder
Lucky Friday Mine, Idaho. McWilliams et. al., (in press); Williams et. al., (in press)	34 geophones and 5 accelerometers, real time acquisition unit, full waveform recording 60-2500Hz HP85 computer, USBM least squares source location algorithm

At the Galena Mine, Idaho, the system which monitors one or two stopes, using 16 geophones per stope is being redesigned to form a mine wide network (Bolstad, (in press)). A new modular system has been designed, using a 32 channel remote data collection unit for each stope, which is fed to an underground instrument room where each unit has an associated processing computer. Data is telemetered to the surface through a fibre optic cable. A vertical, single channel, short period seismograph is located on the surface and the digitised data can be incorporated into the analysis.

Brady (1987) also describes microseismic research at the Galena Mine, the surface system uses triaxial geophones, with associated electronics for the analogue recording of short period seismic events. The analogue signal is split, with one going to a Teledyne-Geotech single axis helicorder and the other being digitised, recorded and

sent by landline to the Denver Research Centre.

Langstaff (1977) describes a 24-channel minicomputer based system used at the Star Mine, Idaho, with rockburst problems. The results were problematical, with occasional seismic precursors to bursts, bursts without precursors and precursors without subsequent bursts. Later work reported by Blake (1984a), was similarly equivocal with only 30% of bursts having clear precursors.

In contrast, Gibbons (1980) has reported events from White Pine Copper Mine, Michigan, in the 25-35 Hertz band can be seen just prior to falls. The link between their occurrence and falls seems rational, as events, with this frequency content, have been observed during monitoring of outbursts at Cynheidre Colliery, UK.

At the Lucky Friday mine, Mullan, Idaho, a system consisting of 34 geophones and 5 accelerometers was deployed throughout the working levels, connected to a real time acquisition system, designed to capture and record all events within the frequency range 60-2500Hz (McWilliams et. al., (in press)). The signals were then processed by an on-line micro-computer which used the U.S.B.M.'s least squares source location algorithm to calculate the location of the events.

Location	System type
Boliden Mine and Laisvall Mine Kreuland and Westerberg (1977)	9 narrow band of geophones
Malmberget, Dannemora and Grängesberg Bäth (1980)	local geophone around the mines. compared with records from permanent seismograph stations.

Limited information is available of microseismic monitoring in Swedish mines with work reported from the Boliden and Laisvall mine (Krauland and Westerberg, 1977) which used narrow band geophones. These systems appear to have been successful recording an increase in activity for about one day prior to roof falls.

Båth (1980) reports that a local geophone array was established around the Grängesberg mine to monitor rockbursts. This enables the discrimination of different types of events by comparing the records with those from permanent seismograph stations.

Location	System type
Mount Isa Lead-Zinc and Copper Mine, Australia Godson et. al., (1980)	32 channel automated system for on-line detection

Again there appears to be limited published data of systems in Australia. Godson, Bridges and McKavanagh (1980) report the initial operation of a 32 channel automated system for the on-line detection and location of rock noise at the Mount Isa Lead-Zinc and Copper mine.

Location	System type
Bharat Gold Mines Limited, Kolar, India Subbaramu et. al., (1989)	14 surface Geospace geophones, 5-180Hz and underground geophones with a frequency coverage of up to 5 kHz FM telemetry along cables, 24 channel analogue tape recorder

In India major rockbursts have occurred in the Kolar Gold Mines, South India, and both surface and underground networks have been used to monitor them.

Two networks have been developed and deployed at the mine of Bharat Gold Mines Limited (Subbaramu et. al., 1989). One is a surface system of 7 geophones used to delineate

zones of high seismicity. The other, an underground array covering a small area, using 7 transducers. A similarly disposed system has been developed at the Indian School of Mines at Bhanbad which incorporates a triaxial geophone deployed on the surface.

3.4 Microseismic Monitoring Systems for Evaporite Mining Applications

Microseismic monitoring systems have been developed and described in Canada and West Germany; summarised in the following tables.

In Canada the major microseismics system have been developed for use in Saskatchewan Potash mines.

Location	System type
Cory Mine, Saskatchewan Vance and Motthahead (1989) Mottahead and Vance (1987)	16 channel underground geophone array, Electro-lab 250MP, link to an IBM-PC Implemented the 'Integrated Acoustic Network' 15 geophones, 1 triaxial accelerometer SIMPLEX locations
Cory Mine, Saskatchewan Prugger and Gendzwill (in press) Gendzwill and Prugger (in press)	6 surface Mark L-1 geophones recorded digitally on cassette tape using Terra-Technology DCS-302 event recorders and played back on an Apple II-plus microcomputer
Saskatchewan, PCS	Terra-Technology DC 232 recorders, surface transducers
K1 and K2, Saskatchewan Gendzwill and Prugger (1987) Prugger and Gendzwill (in press)	5 uniaxial geophones, 1 triaxial set underground, 3 surface geophones. Mark L-1 geophones FM telemetry along cables. Teledyne and Geotech and Springretter equipment. Microseis II system expandable from 16-32 channels
Rocanville, Saskatchewan Vance and Mottahead (1989)	3 geophones on surface, 3 geophones underground, all 6 eventually underground, data analysed on an Apple II microcomputer. SIMPLEX location algorithm.
Saskatchewan	Weir-Jones PC-AT based system, 16 channel

At the Cory mine an Electro-Lab 250MP was used, linked to an IBM-PC (Vance and Mottahead, 1989). The continuing research, included the implementation of the 'Integrated Acoustic Network', a system, using 16 transducers of which 15 were geophones and the sixteenth a triaxial set of accelerometers. Locations are performed by a SIMPLEX algorithm and a cube stepping algorithm. A good correlation was seen to exist between microseismic activity and load (Mottahead and Vance, 1987).

A surface network of six vertical component Mark L-1 geophones were installed above the mining horizon of the Cory mine (Prugger and Gendzwill (in press); Gendzwill and Prugger (in press)). Signals were recorded digitally on cassette tape with source locations being performed by a SIMPLEX algorithm.

The Microseis monitoring system designed at the University of Saskatchewan has been installed in a number of potash mines, for example K1 and K2 (Gendzwill and Prugger, 1987). The system is expandable from 16 to 32 channel and uses much automatic data handling. Source location is accomplished using the SIMPLEX algorithm, first motion directions are plotted for the interpretation of fault plane solutions, and ground motions are calculated. At K2, eight channels were connected to underground transducers, one a triaxial set, whilst three channels were connected to surface transducers. The geophones used were Mark L-1, deployed in pairs underground.

Weir-Jones Engineering developed a Seismic Monitoring System which was deployed in Saskatchewan in 1989, and runs on an IBM PC-AT and uses an STA/LTA trigger algorithm. Initial source location is performed by the Leighton and Blake algorithm, which is then passed to a SIMPLEX algorithm for final source location.

Location	System type
Asse 2, Salt mine. Hente et. al., (1989)	low frequency in the 1-90 Hz band recorded on a paper chart and digital tape high frequency 8 channels in the 45 to 300 Hz band
Asse, Salt mine. Durr and Meister (1984)	single channel system piezo-electric accelerometer filtered output in the 100Hz to 100 kHz band, pen recorder, oscilloscope and tape recorder

In West Germany microseismic monitoring systems have been deployed in the Asse 2 salt mines (Hente et. al., 1989). The system uses both low frequency and high frequency components. The low frequency system is continuously recorded on a paper chart while the high frequency component monitors 8 channels. Source location is performed by the Ingalada method (Cete, 1977).

Durr and Meister (1984) describe the use of system using a single piezo-electric accelerometer for pillar evaluation in a salt mine. Amplitude thresholds were used for event detection and an oscilloscope and tape recorder were used to capture waveforms.

3.5 Systems of Relevance to the Sydney Coalfield

The deployment of a system within the Sydney Coalfield should not only be capable of locating events and displaying the information in a suitable manner, it should also be capable of calculating the whole range of parameters that characterise the source mechanisms of the event.

The location of an event should only be the first step in processing the data and to calculate the source parameters it is necessary to record the full waveform, as the most valuable data is considered to be within the seismograms.

It has been suggested that most of the early part of the coda is associated with scattering close to the source and that the degree of polarization of the p-waves may have prediction possibilities.

Consequently systems previously developed are required to have the ability to record full waveform data to be considered relevant to the Sydney Coalfield. However, other systems which have applicable features are also further considered.

The majority of the systems reviewed have essentially been constructed on an ad hoc basis this should not preclude a similar approach being adopted for the development of a system for the Sydney Coalfield. The reason for the preponderance of custom built systems would appear to result from a lack of adaptable commercially available systems, although the components for the construction of systems are readily available.

Of the systems reviewed a significant number have in their methodology something to offer, to the design of a system for the Sydney Coalfield. Although to generalise, it would appear that no single system would adequately fulfil the perceived requirements of a system to be deployed.

The systems have been critically reviewed to assess their suitability to the specific requirements of the Sydney Coalfield, and these are summarised in the following table.

Systems of Relevance to the Sydney Coalfield		
Mine	System Type	Applicable Features
Campbell Red Lake, Ontario (Neumann and Makuch, 1989)	Electro-Lab 250MP 64 accelerometers PDP 11/23	Deployment of local arrays Full waveform acquisition High speed data manipulation
Macassa, Ontario (Hedley and Udd, 1987)	Gould Waveform Recorder eventually 48 channel with 5 triaxial geophones	Limited, allows first motion studies embodies important concepts
No. 12 Mine, New Brunswick (Kristof et. al., 1987)	Electro-Lab 250MP 32 accelerometers full waveform capture system	Capture of complete waveforms, ability to conduct spectral analysis
Denison, Elliot Lake (Calder et. al., (in press))	Portable, high frequency piezo-electric transducers priority based multi-tasking software	Limited, other than drivages and close to the face Feature extraction and Pattern Recognition
Quirke, Ontario (Semadeni et. al., in press)	Electro-Lab 250MP, a surface system and full waveform capture	Full waveform acquisition triaxial transducers Transmission system
Elliot Lake, Ontario (Labuc and Momoh, 1987)	Masscomp DN5400, triaxial geophones fibre optic links	Monitoring, transmission and processing hardware, spectral analysis. Would require expansion and specialised software.
K1, K2, Saskatchewan. (Gendzwill and Prugger, 1987) (Prugger and Gendzwill (in press))	Microseis II	Limited by number of channels. Applicable location algorithm
Saskatchewan	Weir-Jones Engineering	Limited by sample rate and number of channels, likely to be insufficient

Systems of Relevance to the Sydney Coalfield (cont/...)		
Mine	**System Type**	**Applicable Features**
Galena Mine, Coeur d' Alene, Idaho, USA (Bolstad, (in press))	32 channel modular system with underground processing computer and fibre optic links	Based on a good methodology Modules could be installed around panels. Computers should be moved to the surface
Coal Mines of Western Colorado (Leighton and Steblay, 1975)	Dual frequency system	High frequency monitoring useful in specific locations only
High Frequency Roof Fall Systems (Leighton 1984a; 1984b; 1985)	High frequency system	Applicable only near to the source
Coeur d'Alene district (Hardy, 1987)	20 or more geophones 72 pairs conductor cables	Likely to require more than 20 geophones and signal conditioning
Lucky Friday, Idaho, USA (McWilliams et. al., (in press))	34 geophones and 5 accelerometers Real time data acquisition USBM location	Partly applicable, monitors the mine environment Real time data acquisition
Radbod Mine, Westfalen Mine, Ruhr, West Germany (Will; 1980; 1984a; 1984b; 1984c; 1985; 1989)	MESAS system 32 channel, digital PCM, whole waveform processed	Specifically designed for coal mining applications, with the necessary software. Relevant for panel monitoring
Provence, France (Revalor, (in press))	12 Geophones located on surface and underground, full waveform data acquisition	Ideal philosophy although limited by band width, digitisation rate, and number of channels
West Cliff; Leichardt; Metropolitan, New South Wales, Australia (McKavanagh and Enever, 1980; Grezi et. al., 1984)	Single channel accelerometers in the coal rib	A single channel system is unlikely to be used, although the system showed the applicability of transducers at seam level
Sunagawa, Japan (Isobe, 1974; Isobe et. al., 1976; 1977; 1979;1980; 1984 Sato and Fujii, 1987)	Combined surface and underground system	A combined 3D system should for part of the overall system. Although this is limited by the number of geophones
Horonai; Hiike, (Sato et. al., (1989); Kaneko et. al., (in press))	Panel based systems	This should be considered with a 3D system to form an overall system

Systems of Relevance to the Sydney Coalfield (cont/...)		
Mine	System Type	Applicable Features
Bharat Gold Mine, Kolar, India (Subbaramu et. al., (in press))	Combined surface system of geophones and underground system of accelerometers	This philosophy of a combined system is relevant to the Sydney Coalfield
Polish and Czechoslovak mines	Combined surface and underground systems with a limited number of channels	The methodology is applicable to the Coalfield

The underground systems developed and deployed at the Campbell Red Lake Mine, Ontario (Neumann and Makuch, 1989) appears to be based on a good philosophy, with the use of local arrays deployed through the mine environment. Assuming that the addition of the PDP 11/23 mini-computer, which is reported to have been added to the system to enable high speed data manipulation and processing, affords the acquisition of full waveform data and analysis it would appear that a useful system has been established. The addition of the PDP computer would appear to counter the deficiencies of the Electro-Lab 250MP system already in place. The establishment of local arrays within the overall array is a useful technique. For Lingan this would result in the deployment of a 2D array with local arrays possibly in worked areas, which would either be in position to monitor Phalen, or have to be re-deployed as mining proceeds, and this may not be the most economical way of utilising resources.

The system deployed at the Macassa Mine, Ontario described by Hedley and Udd (1987) whilst as it stands would appear to be of limited applicability the concepts embodied are important. The ability to conduct first motion studies is important and is one of the many parameters required to assist in the understanding of the complex phenomena and this should be applied in the system deployed within the

Sydney Coalfield. Although of limited applicability as it stands the basics could be extended with relevant hardware and software to enable the complete analysis of the available information.

At the No. 12 Mine, New Brunswick, the system is, based around an Electro-Lab 250MP and it was suggested that the capture of full waveform data should be used for research purposes, (Kristof et. al., 1987). A full waveform capture system, was to be installed as part of the research programme, which would enable frequency domain analysis and digital filtering. A full waveform capture system, should form an integral part of any system deployed as opposed to an 'add on' unit. This unit could, however, form part of the system to be deployed within the Sydney Coalfield.

A system that could make a useful contribution to the ability of outburst prediction is that used at the Denison Mine, Elliot Lake. The system employed is a reasonably portable, high frequency data acquisition system operating in the frequency range 50-400kHz (Calder et. al., (in press)) and uses a priority based multi-tasking programme to process the incoming data. This has allowed for precursor analysis of the recorded events using feature extraction and pattern recognition techniques and time and frequency domain computations, unfortunately the analysis did not reveal any significant behaviour. At such high frequencies the range of detection is limited and as such the areas in need of such monitoring would need to be defined (Semadeni et. al., (in press)), or alternatively deployed in development drivages, and be operated in close proximity to the working area as it would be insensitive to man made noise. The problems of recording and processing incoming data has been addressed in this system. The application of software capable of feature extraction and pattern recognition should be considered

for implementation in a system developed for the coalfield.

Whilst the underground system at the Quirke mine, Ontario is based around an Electro-Lab 250MP and a surface system developed by Noranda under a CANMET contract featuring full waveform capture (Semadeni et. al., (in press)). The triggering thresholds and requirements may exclude important information from being recorded when used in a coal mining situation. The problems associated with the lack of full waveform acquisition of the 250MP has been addressed in this system, enabling the computation of important source parameters. It appears that ultimately good quality transducers were deployed, importantly as tri-axial sets and uses and what should prove to be an efficient transmission system. This system uses many features that should be considered, although as it stands it is unlikely to be used.

Labuc and Momoh (1987) have described a similar surface based microseismic system, again developed by Noranda, deployed at Elliot Lake, using transducers installed in boreholes, a fibre optic signal transmission system and analysis on a Masscomp DN 5400. Although a purely surface based system it embodies many of the attributes considered essential to the development of a system for the Sydney Coalfield. From triaxial sensors, through the transmission system, processing software and hardware this represents one of the most applicable systems to monitor the mine environment. Some of the components have now been superseded and it is likely that it would have to be modified for the underground environment, however, it should be relatively straight forward to 'construct' a similar system for underground use from off the shelf components for use in the coalfield.

Another unit that could form part of the acquisition and processing hardware is the Microseis monitoring system, an expandable system of 16-32 channels, now replaced by the Microseis II, designed at the University of Saskatchewan. The system uses automatic and manual phase pickers and uses a SIMPLEX algorithm with ray tracing for event location. This computer based system represents one of the few commercially available acquisition and interpretation systems which could be of relevance to the establishment of a system in the Sydney Coalfield, although it is limited by the number of channels.

A similar system, developed by Weir-Jones Engineering has many features considered necessary for the acquisition and interpretation of microseismic events. The sample rate and the number of channels offered is, however, considered to be insufficient for the data acquisition anticipated in the Sydney Coalfield and it is further limited by an insufficient number of channels.

A modular stope monitoring system, used at the Galena Mine, Coeur d' Alene developed by the U.S.B.M. at the Denver Research Centre, (Bolstad, (in press)) appears to be based on a good philosophy, although designed around a different mining method. Such a modular system could be utilised by deploying the modules around individual panels. It would, however, be preferable to move the individual processing computers to a surface location for such applications, so that a minimum of electronic equipment is deployed underground, this would probably involve the deployment of additional signal conditioning units.

The U.S.B.M. dual frequency system used in coal mines of Western Colorado, monitors in a low frequency band from 15-250 Hz and in the ultra-sonic range, in the 36-44 kHz band (Leighton and Steblay, 1975). The use of the low frequency band supports the usefulness of monitoring events in this bandwidth. Monitoring in the ultra-sonic range as at the Denison Mine is only useful for monitoring over short distances, and as such could be utilised in single entry development drivages in the Sydney Coalfield.

Other high frequency systems have been developed based on high frequency roof fall monitoring systems and have been applied to near source monitoring of outbursts (Leighton, 1984a; 1984b; 1985). The research conducted demonstrated the presence of precursors to outbursts.

The system deployed at the Hecla Mining Company's Lucky Friday Mine, would also appear to be applicable in part, to the problem, it uses transducers deployed throughout the mine to monitor the whole mine environment (McWilliams et. al., (in press)). Importantly the array was connected to a real time data acquisition system to record all events fulfilling certain pre-requisites. However, important information could be rejected, by such triggering, with modifications to both the hardware and software it could be applied to the problems in the coalfield.

The MESAS system, developed in West Germany, is a fully digital PCM underground system, with geophones deployed as packages and signals multiplexed prior to transmission to the surface for on-line analysis (Will, 1985; 1989). The system, although designed for retreat mining operations is suggested to be of use and contribute much to an understanding and prediction of the outburst problem in the Sydney Coalfield.

It is recognised that the system would need to be re-deployed as mining proceeds, and it may be necessary to deploy more than one such system or partition the system to monitor more than one working panel. The difference between this and the many other applicable systems is that the MESAS system is the only one identified which is known to incorporate software specific to the coal mining environment, where highly dispersive waves are generated.

It is considered that the methodology used by CERCHAR in French coal mines in Provence, is most applicable to monitoring seismic activity generated during mining and associated with catastrophic failures. A dual system approach, with one element based on one longwall panel and the other, a larger network, monitoring the mine as a whole, and used for location and focal mechanism studies (Revalor et. al., (in press)). It is suggested that whilst this represents an ideal design philosophy, the system developed, however, should be capable of monitoring signals with a broader bandwidth than specified and should consist of many more transducers to adequately characterise seismic activity. The digitization rate is also considered to be insufficient, but the system benefits from continuous recording of the data.

Another system which appears to be applicable to the anticipated problems of the coalfield was developed in Australia (McKavanagh and Enever, 1980). The system seems to have been successful, recording precursory activity prior to outbursts in the West Cliff Colliery, although it is known that certain problems were encountered in the use of predictive systems in Australia. Unfortunately the system described was a single channel system and as such it is unlikely to be of use for general monitoring, but could be used in specific locations. However it is considered that the methodology of installing transducers at seam level is applicable to the coalfield.

A combined surface and underground system was deployed at the Sunagawa Coal Mine, Japan (Isobe, 1974 and Isobe et. al., 1976; 1977; 1979; 1980; 1984). It was developed to monitor the mine environment and to locate events. It is considered that a three dimensional array should form part of the overall system developed for the Sydney Coalfield. Seismic activity associated with an outburst at this mine was also monitored by a three dimensional array, with anomalous activity associated with the outburst (Sato and Fujii, 1987). This again supports the methodology of deploying an array with a three dimensional spatial coverage to monitor Lingan and Phalen. At the Horonai Mine a district based system has been developed, (Sato et. al., 1989), and it is considered that this should form part of an overall monitoring system. A panel based system was again used at the Miike Mine, with seismometers deployed in the roadways surrounding the panels, (Kaneko et. al., (in press)). This concept of surrounding an area with an array should be considered to form part of the overall system deployed within the coalfield, although it is not anticipated that seismometers would be used for this application.

In the Kolar Gold Mines of Southern India, systems again based on two components have been developed, a surface network is used to delineate zones of high seismicity and an underground network deployed at deeper levels within the mine, monitoring a smaller area (Subbaramu et. al., (in press)). It is considered that the system developed does not use a sufficient number of transducers to adequately characterise the anticipated seismicity generated within the coalfield. However, the concepts of this system should again be applied to the design of a microseismic system for the Sydney Coalfield.

Systems developed in Czechoslovakia and Poland have again been developed to provide three dimensional spatial coverage, with the establishment of both surface and underground arrays. Although these systems have a limited number of channels, the Polish systems have deployed high quality equipment and have met with some success. These systems would again seem to advocate the establishment of both surface and underground arrays, although it is unlikely that these systems themselves would be used.

3.6 Seismic Tomographic Imaging

Although the Seismic tomographic imaging technique is not a passive monitoring system, but an active survey technique akin to in-seam seismic surveys, and strictly not within the scope of this review, it has been included here as it is seen to be a beneficial tool for the location of possible outburst prone areas.

Traditional approaches to the study of mining induced seismic phenomena have concentrated on the use of passive monitoring techniques. However, the use of tomographic images in conjunction with passive techniques to the study of mining is seen to be advantageous.

Conceptually, geotomographic imaging is similar to medical CAT scanning. Tomography can be defined as the reconstruction of the internal structure of a 2D or 3D object from a set of its projections, a projection being a series of line integrals of some physical parameter through the object at a given orientation (McMechan, 1983). It can be carried out on the basis of both compressional and shear wave velocity as well as attenuation. Based on a knowledge of p and s wave velocities, it is then possible to characterise the elastic properties throughout the rock volume.

The travel time for a given ray path being inversely proportional to the average velocity of the rock along the ray path, which is assumed to be straight, the constant of proportionality being the ray path length. The fundamental complication is that the ray paths are not straight where velocity is not constant.

The objective of tomographic processing is to assign slowness values to small discrete areas, pixels, of the area being imaged. Three main algorithms exist to accomplish this:-

- Convolution (filtered back projection)
- Algebraic reconstruction techniques (ART)
- Direct inversion

The imaging of attenuation parameters is exactly analogous to slowness imaging, with the energy levels rather than travel time being measured.

The production of a single two dimensional image carries with it the implicit assumption that there is no variation in the third, out of plane, dimension. At the most basic level such topographic images can be interpreted directly as maps of some spatially varying property within the plane being investigated (Young, 1989).

A small scale, high resolution, survey demands the recording of broad band seismic data. Transducers capable of monitoring frequencies in excess of 1kHz must be utilised requiring the use of high quality piezo-electric accelerometers, or hydrophones, and high quality pre-amplifier systems with a corresponding high cost. It is essential that whole waveform data is recorded for later computer processing, without such a facility neither shear wave velocity nor attenuation tomography would be feasible. Where the Electro-Lab 250MP is used for

monitoring this is accomplished by connecting a waveform acquisition system to the 250MP.

The technique has been used extensively world wide, although not for the prediction of outbursts, and a well documented case history is briefly reviewed here.

3.6.1 Combined Tomographic Imaging and Microseismic Monitoring at the Strathcona Mine

At the Strathcona Mine, Sudbury, Ontario, seismic tomographic imaging techniques have been used to investigate the response of rockburst prone ground to the re-distribution of stresses due to localized mining. The methodology consisted of a hybrid system of concurrent tomographic imaging and microseismic monitoring, already discussed, being carried out at different stages during mining (Young et. al., (in press)).

A low cost whole-waveform acquisition system was developed for use in mine-wide monitoring, and was installed at Falconbridge's Strathcona mine. It was developed to collect three component whole waveform microseismic data, which was stored on a 90Mbyte disk of an IBM (Young et. al., 1987a). Concurrent monitoring was carried out on an approximately 100 x 200m pillar using 36 accelerometers as receivers and seismic blastings caps as sources, with data recorded using a modified 48 channel OYO engineering seismograph as an acquisition system. Images can then be constructed from the recorded data. In general a correlation was seen to exist between changes in seismic velocity, expressed in terms of slowness, and the location of microseismic activity (Young et. al., (in press)). It was hoped to monitor microseismic activity in the volume using 5 triaxial sensors (Young et. al, 1987a).

Tomography provides an opportunity to investigate large volumes of the rock mass remotely and this is particularly useful for detecting variations in a rock mass, both temporarily and spatially. It can be used to investigate the response of the rock mass to mining and to identify anomalous ground conditions ahead of the face. Images can be constructed using a traditional filtered back projection technique, to produce a rough image based on straight ray theory. A second stage can then be implemented where ART is applied to refine the image.

The build up of anomalous stress conditions are a clear safety concern in underground mining because of their significance in rockburst phenomena. Repeated imaging allows for the monitoring of changing geotechnical parameters resulting from a dynamic stress regime. Any large scale changes in stress or rock mass quality may be monitored through time as the mine envolves, utilising such imaging. Such a programme would, therefore, be a logical extension to existing microseismic networks.

4. SYSTEM DESIGN

As mining proceeds to greater depths the underground coal mines of the Sydney Coalfield are considered to be at considerable risk from the occurence of outbursts, which were the cause of serious problems at the No. 26 Colliery. It has been shown that all outbursts that have occurred in the Sydney Coalfield have occurred where a sandstone erosion channel has been present within 2.7m of the top of the coal seam. The problem is considered to be serious as palaeo-lithic fluviatile channels cross the proposed workings of the Lingan mine specifically and the coalfield in general. Consequently research has been conducted on modelling of the outburst phenomenon and assessing the feasibility of preventative techniques. Little work had, however, been conducted on predicting outbursts. In order to attempt to predict the phenomenon the technique of microseismic monitoring has been assessed and what is considered to be an appropriate system has been designed, and is discussed in Section 4.3.

To elucidate the phenomena the system designed should, at the very least, be capable of recording and capturing full waveform data for further on-line, real time processing and also off-line processing. The system should provide:-

- the location of areas of high microseismic activity both in event rate and energy released to indicate zones of high stress and indicate changes in the temporal and spatial distribution of the activity.

- the ability to investigate the mechanisms of outbursts by first motion studies, seismic energy, spectral frequency analysis and peak particle velocity.

- discrimination of the onset of abnormal activity either in type or intensity presaging the onset of outburst conditions.

- Real-time information to Colliery Management to allow decisions to be taken as to
  - Advance Rate
  - Face halts
  - when to implement Inducer Firing and assess its efficacy
  - Resumption of cutting after incidents

- Confidence to mine personnel and hence reduce psychological stress on those men working at risk from Outbursts.

To fulfill these objectives it must be capable of on-time and off-line processing and analysis. Furthermore, full waveform data should be recorded for further analysis and research purposes. The recording and analysis section of the system should therefore:-

- be capable of data throughputs of c 100,000 samples/sec

- be capable of automatic event detection and storage, with sophisticated triggers (STA/LTA, Murdoch-Hutt or possibly more tailored to Channel waves) and coincidence windows for off-line analysis, seismic moment, s-wave polarisation

- be capable of archiving continuous data if possible for research purposes. This would probably require a separate VCR based digital recorder to accomodate the data rates.

- be capable of on-line event location for both dispersive channel waves and normal body-waves.

- be capable of evaluating seismic energy density plots.

- present information in a way which is readily available to mine management. This will probably be via two and three-dimensional contour maps and perspective views on a colour high-resolution graphics work-station, eg SUN-SPARC or MASSCOMP UNIX Machine)

With this information it should then be possible to keep mine workers and supervisors informed about the locations of abnormally high event rates. These areas could then be inspected and treated with greater caution and if destressing techniques are to be used these could be implemented. It should, therefore, be possible to give confidence to mine personnel and reduce the psychological stress on those at risk. In the event of false alarms, we have found that confidence in the systems has not been lost in the UK. An alarm issued is generally caused by a 'real' abnormal situation existing, be it either an outburst condition or stress concentration, resulting from ground support problems or even the roof hanging. In either case measures can be implemented so improving mine safety. Also in the UK, once outburst conditions have been flagged, the situation does not normally culminate in an outburst occurring as destressing techniques and methane drainage are implemented.

4.1 Design Criteria

The design and development of a monitoring system should be based on the characteristics of the microseismic

activity at the site and the nature and severity of the problem.

The components selected should be matched to the characteristics of the rock noise events generated. It is therefore, necessary to assess the constraints placed on a system by the mine or site, and the cultural background noise so that problems of interference can be eliminated or minimised. The nature of the rock stability problem must also be considered. The degree of sophistication of the system will depend on the severity of the problem.

A test programme should be implemented to select the appropriate components of a desirable microseismic monitoring system, which should have the capability of determining (Blake 1984b, 1987).

- frequency of the microseismicity
- amplitude range of the microseismicty
- attenuation and propagation characteristics
- accurrate seismic velocity model
- background and cultural noise characteristics

A microseismic monitoring system can broadly be divided into three major components which are:-

Transducers	**Amplification Transmission System**	**Recording Discrimination and Analysis**
Seismometers Geophones Accelerometers	Sinal Conditioning Radio-Telemtry PCM Cabling Optic Fibre Links	Chart Recorders Tape Recorders PC Based Unix Work Station Hard Wired

The development of a suitable montoring system necessitates the following (Hardy in press, 1986).

- selection of the most suitable transducers
- development of the most efficient installation technique
- selection of an appropriate telemetry system between sensor and monitoring facility
- design of a stable and sensitive monitoring facility
- selection of hardware and software for recording, event location and analysis
- detailed field studies to evaluate ambient field/site conditions to optimize the monitoring system

From the information gained from field studies the following factors should be considered in the selection of transducer sites:

- the location of areas to be monitored
- available access
- the number of areas to be monitored
- the desired source location accuracy
- necessary 3D geometry to permit accurate location

Seismic Sensors

Typically microseismic monitoring systems use either geophones or accelerometers to detect acoustic signals, although seismometers are often used, mainly in surface applications. It is also possible, however, to use pressure transducers. A comparison between the two more usual sensor types is included below:-

	Geophones	Accelerometers
Cost	Moderate	Expensive
Robustness	Very robust	Fragile
Output	High	Low, needs extra electronics not IS
Dynamic Range	High (140dB)	High (150dB)
Response to large events	Poor	Good
Low frequency (<30Hz)	Poor	Good
Mid-Range (30-3kHz)	Very Good	Moderate

In a coal mine environment where robustness and simplicity ar paramount and where the sensors may be lost it is considered that geophones are the best option. The various sensors types are further discussed herein.

Geophones detect the particle velocity of ground motion in the direction of the axis of the geophone. Accelerometers detect the particle acceleration in the direction of their sensitive axis. Pressure transducers are not sensitive to direction, which is an advantage, but they must be immersed in a liquid which is coupled to the rock, in a borehole for example. Most microseismic systems use either geophones or accelerometers.

The low output of piezoelectric accelerometers requires that they be used with a sensitive pre-amplifier. Accelerometers tend to have a wide dynamic range, up to 150 dB, and a large frequency range. They respond well to high frequencies and can record larger amplitude ground motions than geophones. However, accelerometers that are capable of responding to several g's of motion near a large rockburst, do not have sensitivity for the smallest ground motions.

Geophones have a relatively large output and do not generally need pre-amplification. Their maximum output being limited by the maximum coil movement, although their dynamic range may be in the range of 140 dB. Geophones tend to be more sensitive than accelerometers at the lower frequencies. Geophones are less expensive than accelerometers.

Geophones may be the instrument of choice for mine wide monitoring systems where it is important to detect weak signals originating far from any geophone. Accelerometers may be better for high resolution surveys of small, nearby events, or for large events where a geophone may saturate. High gain amplification may saturate and clip large signals, whilst smaller signals may not be registered by low gain amplification. However, the problem may be solved by using dual amplification with both high and low gains or alternatively gain ranging ampliers.

Decisions have to be made at an early stage as to the selection of the transducers with regard to the perceived goals of the monitoring system. However, regardless of this, the transducers selected should have a wide dynamic range. It is also considered that 3 component sensors should be utilised wherever possible to allow for the application of digital polarization filtering for the enhancement of p and s-wave arrivals. For long term monitoring the transducers selected need to have suitable stability, both electrically and mechanically and should be capable of being remotely calibrated. A suitable and reliable power source is also required, which generally implies access to a power supply. The whole system needs to be secure. If data is recorded, personnel are required to change the tapes and charts. Personnel and facilities need to be available for both regular and emergency maintenance, repair, and calibration of the overall

system. Clearly these selections are both site and goal specific, and should be based upon the results of an initial test programme. There are then questions as to the amount and type of conditioning that is required, if any, prior to transmission, and whether the system should be analogue or digitial. Filtering is often used to remove undesirable low and high frequencies signals.

The geometry and size of the transducer array imposes limitations on the selection of system components. It has been found that in most applications an array of six of seven transducers is optimal. With such an array the source to transducer distance increases, which results in increased attenuation of the signals, and as attenuation is frequency dependent, the basic frequency content of the observed signals will be decreased. The former results in a low signal to noise ratio and the latter results in difficulty in evaluating event arrival times and subsequent degradation of source location accuracy.

Telemetry

Telemetry is the means of transferring data from the sensor to the recording and analysis system. the signal must be transmitted with minimum loss of strength, with no additional noise, with as wide a bandwidth as possible and without a phase shift. In some cases signals can be multiplexed, transmitting several signals on one cable. The choise of telemetry method is effectively between four techniques.

- Standard Cabling (Analogue Signals)
  Is cheap and readily available but introduces delays, is very noisy and signal losses are large. Intrinsically Safe.

- Optic Fibre Links
  Are expensive and not readily available in Intrinsically Safe specification. Very low noise, and very high bandwidth.

- FM Telemetry
  Low cost, but low bandwidth, moderate noise, readily available. Intrinsically Safe.

- Digital Telemetry (PCM) down standard cable moderately expensive, good bandwidth, low noise.

Some telemetry systems introduce significant time delays and it is essential interpretation of the data that a time reference is for the used so that arrival time of signals with respect to each other can be identified with high accuracy, usually fractions of a millisecond.

An acoustic emission system typically will be used to monitor only a small volume of ground for a relatively short time and the entire recording system may be placed near the monitoring site. The telemetry for an acoustic emission system may therefore be only through short wires. Often such systems are used in drill holes so telemetry must be through a downhole logging cable.

Cabling the transducer output to the central monitoring facility has always been a problem. For a close centrally located monitoring station, it is possible to run individual cables. However, for a monitoring facility situated on the surface or at an underground shaft station it is necessary to run a trunk line to junction boxes. Cable should be of high quality, water proof, have a high tensile strength to resist stretching or breaking and should preferably be armoured.

However, transmission can be down a single wire pair (such as telephone transmission lines), coaxial cables, or fibre optics. There is always a problem of transmitting data along cables over long distances in an electrically noisy environment. Standard telephone transmission lines also have delays of 4 - 8 micro-sec/km and compensation should always be applied, prior to demodulation, to avoid signal distortion. They have a minimum precision of 0.1% at 7.5 kHz.

For high rates of transmission, buffered operation can provide for a multichannel microseismic system, which can handle data rates in excess of 5 events per second at a digitizing rate of 20kHZ. The problem of absolute time then appears with the use of buffered operation and a time correlation system is then essential.

The next most sophisticated telemetry system is with frequency modulation (FM). With FM systems, a voltage controlled oscillator (VCO) uses the amplified geophone signal to modulate a high frequency (less than 10kHz) carrier wave. Several (up to 8) carrier frequencies can be sent on the same wire, separated by a filter at the other end, and demodulated, recovering the original geophone signal. The FM signals can also be sent on voice grade radio. FM systems can transmit data with much less distortion and noise than can analogue systems. However FM systems typically have less dynamic range than analogue systems. The Sprengnether VCO model TC10 is restricted to 56 dB at 25 Hz bandwidth, Lennartz VCO systems are only 50 dB. With some systems it is possible to increase the range at the cost of transmitting fewer channels per wire. As with analogue systems, special low gain channels must be used to record large amplitude signals. FM systems are adequate for many regional seismic monitoring programmes. The advantage of FM telemetry is its low cost and low

distortion within the rather limited dynamic capability.

Digital telemetry, where digitization occurs at the geophone, is a step up in complexity, performance, and cost compared to analogue or FM systems. However, for the improved performance, high quality digitizers must be used. The common 12 bit digitizers have only 72 dB of gain, barely matching analogue amplifiers. With gain ranging amplifiers, 16 bit digital systems achieve 132 dB, matching the dynamic range of many geophones and some accelerometers. The output can go directly into a computer. However, difficulties arise at high sampling rates. At 1,000 samples per second (adequate for a 250 Hz signal), a 16 bit word requires 16,000 bits per second (baud rate) per channel. This rate is near the limit for voice grade communication systems so if several channels are to be transmitted on one wire high quality transmission equipment must be used. Such baud rates taxes the capacity of common serial ports on microcomputers, so special data ports must be used to record multiple channels or faster sample rates. Even so, the digital data stream respresents an enormous amount of information to handle so that a large capacity computer is required. Some proposals have been made to use a small computer at each geophone and only transmit data when the computer recognizes that a seismic event has occurred. This can be done provided that there is two way communication between the central computer and each outstation for control and time information.

Recording Systems

Recording systems vary widely in cost and ability. The simplest may be the single channel paper chart Helicorder variety driven directly by an analogue signal. These are reliable and provide continuous, direct records for

immediate visual examination. Problems involved are that much manual work is needed for interpretation, and the dynamic range is small, typically only 40 dB, so that the record "clips" on large signals. A helicorder is, however, a very useful adjunct to a computer system for quality control. Many seismic monitoring experiments have been performed using portable helicorder units because of their ease of use in a "fly in" situation. Accurate time control is often a problem with helicorders.

Seismic data can be recorded directly on a tape recorder for playback later. This has the advantage of a somewhat larger dynamic range than a paper record and it can be played back at different scales or dititized. Such analogue tape systems are labour intensive and suitable only for short monitoring programmes.

A wide variety of computer controlled systems are available. Most systems receive analogue signals, digitize them in the computer, and store the data. Most systems now have some type of temporary memory (buffer) and an event recognition scheme that analyzes data in the buffer so that only recognized events are transferred to permanent storage. This has the advantage of reducing storage requirements but may miss important events due to limitations of the algorithm. Usually, a short sample of background noise that occurred immediately before the event is also transferred from the buffer to premanent storage.

A variety of filtering and event recognition routines are available. The simplest trigger is an amplitude threshold; if the signal level exceeds a set value of one channel, the channel is triggered. The simple amplitude threshold does not work very well if there is background noise or a D.C. offset in the amplifier. A better trigger

is the STA/LTA ratio (Short Term Average/Long Term Average). These represent average signal amplitudes taken for a short time, a fraction of a second, and for a longer time, perhaps several seconds. The signal is first corrected for any D.C. shift. When the ratio of STA/LTA exceeds some preset value, the channel is declared triggered. The advantage of the STA/LTA method is that it adapts itself to moderate noise levels. Other more sophisticated methods can use changes in frequency or the statistical character of the noise to trigger on but these are often too complicated to implement in real time on a small computer. Multichannel systems can require certain numbers of channels to be triggered within a certain time interval before a valid event is declared. There can also be external triggering under the control of the operator, a clock, or another machine.

Data Collection Systems Without Interpretation

These system are powerful digital data collection systems but contain no internal interpretation capability. The manufacturers may provide an interpretation package that runs on an auxiliary computer, after data is transferred, but some users may prefer to write their own interpretation programmes. By linking several of these small units together and adding telemetry, good mine monitoring systems could be designed.

One of the more powerful modern systems is the Teledyne Geotech PDAS-100 system, which is capable of digitizing three channels at 1000 Hz or six channels at 500 Hz. Eight of these PDAS units can be linked together. Triggering can be controlled by an operator, a clock, another machine, or an algorithm. Four different event recognition algorithms can be selected, testing trigger conditions on any specified combination of channels within

selected time windows. The trigger tests can be done on filtered data, if desired, while still storing unfiltered data, if desired. The filters are programmable. The system has a 16 bit digital converter which can be used as either fixed gain or gain ranging for up to 132 dB of dynamic range. It can hold up to 12 megabytes of RAM storage. Data transfer is iether serial or parallel, so data can be telemetred via modem or dumped into a computer. An external computer can communicate with the PDAS computer. PDAS has a battery power supply that will last for a week or it can run on a charger. Power is provided for accelerometers. The unit is in a rugged case designed for mines and other harsh environments. Recorder and battery weigh 19.1 Kg. The system is designed for data collection only and has no display or interpretation capability. Cost is of the order of $12,000. PDAS systems have been tested in Saskatchewan mines.

Terratechnology offers their IDS-3602 (Integrated Digital Seismograph) which includes three channels sampled at 1000 Hz with 16 bits gained ranged 132 dB. The anti-alias filter is set for 70 Hz. Low pass digital filters can be set at 10, 20, 30, 40, 50, 60 or 70 Hz. Several units can be linked together. It holds up to 6 megabytes of memory. There is a choice of STA/LTA or amplitude triggering. Set up and data transfer are with an IBM-PC compatible computer through a serial port. Batteries will last for four days. The system is in a rugged case and weighs 8.6 Kg. It is designed for data collection only and has no display or interpretation capability. Basic cost is of the order of $8,000.

Sprengnether offers their DR-2000 solid state portable digital recorder. This features three or four channels sampled up to 800 samples per second with 15 gain ranging bits for 120 dB dynamic range. It can hold up to 6

megabytes of memory. There is a choice of STA/LTA or amplitude trigerring. The unit has both parallel and serial ports for control and data transfer to a PC. The DR2000 has no display or interpretation. It operates on a battery or A.C. current. It has a rugged case and weighs 8.2 kg without battery. The cost of this system is about $6,000.

Kinemetrics also has a three or six channel field portable system, the SSR-1. It records 500 samples per second on three channels or 200 samples per second on six. It has 16 bit fixed gain A/D for 96 dB dynamic range. It has plug-in filters of 5, 15 and 50 Hz. It can hold 1 to 4 megabytes of data. Triggering is with threshold, STA/LTA, clock, or external and several units can be linked. The unit comes in a waterproof field case, it runs on a rechargable battery, and it weighs 17 kg. The system can power accelerometers. With control and data transfer being through a RS-232C serial interface to a PC computer. No display or interpretation is, however, done in the SSR-1. The basic unit sells for about $10,000.

Systems with Interpretation

These systems are offered with a combined digital data collection system and an interpretation software package on the same computer and are designed for the office environment.

Sprengnether has a high end system called PC-MDR, a PC based multichannel digital recorder. It has 50,000 samples per second throughput with up to 500 samples per second per channel at 16 bit fixed gain for 96 dB dynamic range. It can be expanded to 256 channels at lower sampling rates. It includes a 20 megabyte hard disk and a 20 megabyte Bernoulli disk, a parallel port and two

serial ports. It uses STA/LTA or threshold triggering. This system features on-line preliminary event location and it can display the last captured event waveform. However, it is intended that the data should be transfered to another computer for final analysis. Sprengnether offers their PC-DAC seismic workstation for such analysis. The PC-MDR is not rugged, it looks like a PC, and requires an A.C. power supply. A 16 channel system is priced at about $25,000 and is supposed to be available in 1990, cables are extra.

The most widely used seismic monitoring system in North American mines is the Electro-lab model 250MP. The design is based on work done by the U.S. Bureau of Mines in Idaho and elsewhere. The 250MP series system is described by Electro-lab as a high speed data acquisition system, designed as a research tool, having the ability to locate microseismic events in underground or surface mining environments using a source location algorithm developed by Leighton and Duvall (1972).

The digital computer within the system measures the arrival times of the microseismic events, when the signal exceeds a preset threshold and the 254 timer is used to reject spurious events or those occuring on too few channels. The source locations are calculated along with the velocity associated with the event, the size of the event and its time of occurrence. No further analysis of the data is performed and it does not, therefore, have the ability to predict outburst or rockburst conditions. The system has the ability to store up to 100 events, and printing of source location and timing information will be suspended by the priority based software to capture an event.

Triaxial sets of type 271 accelerometers are used which have a flat frequency response over the range 100Hz to 10kHz. It has been designed so that a minimum amount of electronics is deployed underground, with only the accelerometers being installed underground in a three dimensional array. An underground power supply is not required as power is supplied from the 2577 power supply in the 250MP equipment rack. Cables used for telemetry must comply with REA cross talk standards.

The 250MP system consists of a 251, which handles all data I/O and system peripherals and a 252 processor which is dedicated to source location calculations, a 254 timer, a 257 calendar clock which provides event timing and the system rack which also contains the power supply unit and a 250A filter. The rest of the equipment is channel dependent. A 2551 input card and eight 250A filters are required for each 16 channels. The 250A filters are used to filter the seismic signals, and provide two modes of linear signal filtering and three modes of triggering. The basic rack and power supply can be configured for 64 channels, however, it is possible to configure the system to 250 channels. If the size of the event is to be determined one of two integrators will also be required. Either the 2510 integrator, which requires the use of 1125 transducers or the 256 integrator which can be connected to any of the accelerometers in the array.

The MP250 has been described here, as it could be considered for use as part of the system to monitor the mine environment. However, it is considered that it will not be applicable for the detailed panel-based system. If the MP250 was to be considered for use to monitor the mine environment, it will be necessary to install an additional computer, either an IBM PC or perferably a MASSCOMP for digital storage and analysis. Alternatively series 400

multiplexers and storage units could be considered. Recently, some experiments have been carried out in Ontario mines to digitize the accelerometer outputs and record waveforms with another computer.

The use of this system is not recommended as it use would necessitate the acquisition and use of a powerful computer to fully analyses the available data. A computer such as a MASSCOMP should be capable of carrying out all required functions. Specialized software is also required for this application which does not appear to be available within the 250MP System.

Evaluation of Source Location

One of the many aspects of processing is the evaluation of source locations. To achieve an accurate source location one of the most critical factors is the development of a realistic velocity model of the mine. There exists a plethora of source location techniques, which also need to be evaluated so as to obtain an accurate location. Some of the algorithms for source location are:-

- U.S.B.M. least squares
- SIMPLEX
- Diminishing cube
- Simplex combination
- Time-difference-method
- HYPO71

The direct solution uses a series of linear equations to solve, for the 3D solution, plus velocity. Least square versions of this technique have been developed by the U.S.B.M. and Mount Isa in Australia.

Non-linear iterative techniques are widely used in seismology when linear methods cannot be applied. These include direct search methods when only the value of the object function is used; for example SIMPLEX. Gradient methods which use the first derivative of the object function for example NEWTON LEAST SQUARES and methods with higher orders of the derivative; such as DAMPED LEAST SQUARES with second order corrections (Niewiadomski, 1987).

When the complete waveform is recorded the separation observed between the p and s waves can be used to calculate the source locations.

The computation of locations is generally based on the first break information of the p wave arrival, although, some authors have used the first peak amplitude arrival times, considering that this better represents the nature of the source.

It is, however, always desired that the true source is uniquely determined. To obtain this, most location theories assume that the stress wave originating at the source travels to the transducers along straight ray paths. Clearly this is rarely the case.

It has never been theoretically verified that by solving a set of quadratic equations, based on the time difference approach, provides such a result. Work by Cete (1977) at the Ruhr University in Bochum, West Germany implies that commonly used source location methods, such as the U.S.B.M. least squares method, probably loose a physically feasible solution. Physically feasible implies that the solution must be in the real domain and satisfy all arrival time differences. Multiple solutions can be produced and this is a phenomenon closely related to

transducer array geometry.

There also exists many different ways of presenting microseismic information. Location plots can be constructed in many different ways, day to day, time period plotting, cumulative plotting, point plotting and rock noise density plots. Point plotting plots the points at the actual solution co-ordinates and is best used to define areas of short term or rapidly developing potential failure areas. Contouring on the other hand is not so precise but has the advantage of producing a clearer picture of the approximate centre of the problem area. Source location concentrations are best detected by using cumulative plotting in combination with contouring.

The design criteria for seismic networks are continually changing with the evolution of electronics. One cannot, however, fail to be impressed by a state-of-the-art network utilising 3D colour displays of the source location of an event. However, it must be realized that the location of an event should only be the first step in processing the data.

The most valuable data is contained within the seismograms and they should be fully analyzed. It has been suggested that most of the early part of the coda is associated with scattering close to the source and that the degree of polarization of the p-wave may have prediction possibilities. It is therefore, considered, that a full investigation of the microseismic events should include the whole range of parameters characterizing the source mechanism of the event, and not just the source location.

4.2 Appraisal of the Applicability of the Systems to the Outburst Phenomenon in the Sydney Coalfield.

Descriptions of the nature of the outbursts experienced at No. 26 Colliery, where they occur in channel sandstones, seems to suggest that they are a consequence of the superposition of three main effects:-

i) Induced tensile stress due to static stresses
ii) Induced tensile stress due to shotfiring
iii) Pore gas pressure

The majority of the outbursts that have occurred in the No. 26 Colliery occurred in development headings, driven in virgin coal, with the majority occurring after shotfiring. However, as the shot can only be the final trigger to the onset of the event, the conditions predisposing the area to outburst must be already in existence. The presence of discing in some sandstone suggests that the stress condition is conducive to fracturing of the sandstone close to the underground opening and it seems likely that the stress re-adjustment close to the opening will be accompanied by acoustic emissions. The occurrence of outbursts when the sandstones were within 2.7 metres of the seam or about 0.5m of the top of a roadway, suggests that acoustic energy generated by fracturing will couple into the coal seam as a guided Love wave mode. In fact, for frequencies below about 200Hz, the bulk of the energy in guided waves travels in the strata bounding the seam. As a result of our experienced with monitoring in boreholes in advance of faces, it seems likely that it will be possible to detect any seismic events at considerable distances. Based on the surface seismic work carried out by Kusznir et. al., (1984) and Westbrook (1980), as well as the Cynheidre monitoring carried out by Styles et. al., (1987), it also

seems that enough energy will reach the surface to register on suitable detectors.

Most of the systems which were described herein have been deployed as research tools and have either been constructed by the group themselves or assembled on an ad hoc basis by the researcher to fit his own requirements. These have been critically reviewed in Section 3.5 and whilst many have been based around a good methodology they mostly appear to satisfy only a part of one of the required elements for the Sydney Coalfields, for example the methodology of the French system would appear applicable, although it is limited by both the number of channels available and the bandwidth of the system. There are very few systems available which are tailored specifically for mining, the exception to this being the MESAS system which seems to fulfill the requirements of one of the envisaged elements of the system to be designed for the Sydney Coalfield and is discussed in Section 4.3.2. If full use is to be made of the data, including polarisation analyses, seismic moment studies, accurate hypocentral locations, a digital system is essential. This does not simply mean a computer-based trigger system which detects events, calculates the p and s-wave onsets and then calculates a hypocentral location without saving the waveform for further analysis. While this information is extremely valuable in itself, the enormous amount of work carried out on mining seismicity shows that these parameters, by themselves, are unlikely to reveal precursors to outburst without some analysis of the nature of the events and their significance. It is especially important to have a broad bandwidth, as low-frequency emergent events have been useful indicators of mine stability in hard-rock mines, (Gibbons, 1980), Potash mines (Wong, 1984), and in coal mines (Styles et. al., 1987).

If it is logistically possible, the evaluation undertaken would seem to suggest that a hybrid system using surface seismometers and an underground array would provide a technique to target areas for the deployment of a panel based system. Such a hybrid system would provide the most flexible and broad band system, with data being acquired by a fast real-time computer, having the capability of storing whole waveforms from a multi-channel system. In sections 4.3.1 and 4.3.2 the proposed design of these two components of the system are outlined. It is also considered that tomographic studies could be utilised to determine areas where stress concentrations exist. It would also have the ability to investigate the response of the coal seam to mining and to identify anomalous ground conditions ahead of the face.

It is understood that the majority of outbursts that have occurred within the No. 26 Colliery occurred in development headings when sandstone erosion channels were present within 2.7m of the seam or about 0.5m of the top of the roadway and the majority were initiated by shotfiring. Similar circumstances were observed in Cynheidre Colliery, UK, in which single entry headings were outbursts prone. The perceived danger of outbursts in coal or stone headings was obviated by applying a Code of Practice to the shotfiring which strictly governed its implementation over a distance of 30 metres of the face. In such areas microseismic monitoring systems could be considered. It would appear that these would have to be high frequency systems such as those described by Leighton (1985) which are insensitive to man made noise. It is considered that such a system, probably single channel, could form part of the overall system, but it is unlikely to elucidate the mechanisms of outbursts required to construct a predictive capability for the mine as a whole.

4.3 Design of a Microseismic Monitoring System for the Sydney Coalfield

One of the requirements of the Statement of Work is the development of a detailed methodology for the establishment of a microseismic monitoring system capable of monitoring microseismic activity associated with the phenomenon of outbursts to lead to the prediction of outbursts within Sydney Coalfield. The design of such a system is addressed in this section. It must, however, be emphasised that some of the precise details can only be finalised after the completion of a rigorous test programme to determine the characteristics of the seismicity.

In order to characterise mining induced seismicity and that associated with outbursts and to develop an understanding of the microseismicity leading to an outburst so that a predictive capability could be formulated, it is considered that it would be necessary to deploy a hybrid system of a three dimensional whole mine environment monitoring system combined with a local panel based system. The detailed design of the components of this system are discussed in the following sections. However, if a phased approach is to be adopted rather than deploying the complete system it is considered that the emphasis should at first be applied to the establishment and operation of the mine environment monitoring system, which would maximise the available resources.

4.3.1 Monitoring The Mine Environment

To characterise adequately both mining induced events and events associated with a gas outburst, it is necessary to surround the mining environment with a three dimensional array (Styles et. al., 1987). To obtain the three

dimensionality required, it is necessary to install a surface network where possible, combined with a mine wide microseismic system. It would also be an advantage to install a system below the mine to be monitored. This is normally difficult to achieve, however, in this instance, the presence of the Phalen workings, which are being mined progressively deeper under the Lingan workings makes it possible to establish combined array that would surround the Lingan workings. The major drawback in this methodology is that it is conceptually difficult to establish a conventional surface array, as the workings extend beneath the sea. However, existing technology, would make the establishment of a 'surface' array, albeit underwater, practicable.

The establishment of a three dimensional monitoring network would assist in the accurate location of microseismic activity, induced by mining or associated with outbursts if such conditions are encountered. It will also allow for the delineation of areas where there is a build up of a stress concentration. The delineation of a localised area where the levels of activity rise to a level which is indicative of the onset of outburst prone conditions would allow the rapid deployment of the detailed panel based monitoring system (described in Section 4.3.2.), if this has not already been established.

4.3.1.1 Deployment of Transducer Arrays

The proposed design for a network capable of monitoring the whole mining environment takes full advantage of the position of Phalen with respect to the Lingan workings. It also takes a somewhat novel and original approach to the establishment of a 'surface' array.

Surface Monitoring System

To maintain a three dimensional array which is necessary for accurate locations we propose in this design to establish ultimately an array of 5 ocean bottom seismometers (OBS). However, it would be prudent to conduct a pilot study of this element, to ensure that such an application is appropriate.

Ocean bottom seismometers have been used routinely in seismology and the technology has been well tried and tested through time. An OBS is simply a triaxial seismometer package enclosed in a pressure case with gimbal mounting which is lowered to the sea floor. Land based surface microseismic monitoring systems have also extensively employed standard equipment used in seismology. They have been used to great effect, having the capability of not only monitoring mining induced seismicity, but also activity associated with outburst conditions. They have also been used to predict outbursts conditions. The use of an array of OBS's has the advantage that it does not have to conform to the requirements of intrinsic safety regulations of coal mine environment and would assist in establishing a three dimensional network. It is recognised, however, that there are problems associated with the use of an OBS array.

The OBS array should be deployed in deep enough water so that wave generated noise does not affect the seismometers. If this condition is satisfied, the sea floor environment is extremely quiet seismically and provides an ideal site for monitoring low level seismicity. However, it may prove that an umbilical cable connecting the OBS to a buoy maintained on station, is a source of noise, again this should be addressed in a pilot

study. If having conducted a pilot study a full OBS array is to be established, it should be deployed in the form of cross configuration with a central OBS, and they should be deployed in such a manner that they will have the ability to monitor the entire mine, both present and projected working areas.

It is envisaged that 'pop up' OBS systems should be used, fixed with remotely activated explosive bolts to the mounting frame, so that in the event of storm damage or the need to repair them, they could be retrieved. Clearly logistic problems exist in servicing such an array. However, significant advantages are envisaged if such an array was to be installed and it functions correctly.

While transmission path between Lingan and the proposed OBS array would be good, the transmission path between Phalen and the proposed OBS array is somewhat more complex with the presence of Lingan workings in the transmission path which would cause scattering.

It would be necessary to transmit data, either by radio telemetry, or micro-wave links. This would entail the need to maintain buoys, on station, equipped with both a power supply to power the radio telemetry equipment and the seismometers. The maintenance of the buoys and the ability to maintain station are problems that should be addressed in a pilot study.

Whilst the ability to transmit data from buoys maintained on station is at this stage conjectural and could only be tested by a pilot study it would seem prudent to considered an alternative method of obtaining the required 3 dimensionality. This requirement is partly afforded by the deployment of an array of geophones in the Phalen colliery discussed under the heading 'Underground

Monitoring Systems'. Full 3 dimensionality could alternatively be established by deploying geophones, either as triaxial packages or as single geophones in boreholes. The boreholes would be required to be drilled up from the Lingan workings, assuming that an aquifer is not present above them. This is likely to entail the drilling of many boreholes to form a cross configuration with additional boreholes drilled as and when necessary to maintain coverage of the workings as mining progresses. Alternatively horizontal or subhorizontal boreholes could be drilled for geophone deployment, although it is likely that these holes would be of somewhat greater length, although they may be somewhat easier to drill, and it is also likely that it would facilitate the deployment of geophones somewhat easier. The main problems with this form of installation is maintaining the correct attitude of the geophone axis and installing the geophone packages in the correct position in the borehole. Telemetry of the signals from the sensor to either an underground conditioning unit or alternatively the surface would be by cable, preferably armoured, to protect the in-hole transmission system. It is again suggested that this element should be tested during an initial pilot study.

Underground Monitoring Systems

An underground network should be established as the major part of the system, with elements of th array being deployed in both Lingan and Phalen. If an array was to be established only in Lingan, a 2D array would be produced, but by using the Phalen workings as well, three dimensionality could be maintained. There are several advantages of using both mines. The establishment of an array within Lingan itself is not only of use for monitoring Lingan but will also be in place to monitor

Phalen as its workings approach the depths at which outbursts were experienced in the No. 26 colliery. Similarly the deployment of transducers in Phalen will assist in the monitoring of Lingan and are essential to the monitoring of Phalen itself.

A mine wide array should be established in both mines with a large inter-geophone spacing. It is considered that a spacing of 750-800m between geophones should be employed in the down dip direction. This equates to deploying geophones every 3 or 4 panels. The spacing of the geophones along the panels ideally should be of the order of 1400m, unfortunately if this spacing was rigorously adhered to, this would place one of the transducers in close proximity to the haulage roads. Such positions would inevitably lead to the contamination of the seismic signals by noise generated by underground haulage rolling stock.

The underground array has been designed with a minimum of three geophone locations, and preferably four geophone locations with triaxial sets installed where possible, being deployed across the mine at intervals of every 3 or 4 panels in the down dip direction. An area of Lingan, with possible geophone locations is schematically shown in Figure 2.

To construct a good array of geophones within Lingan consideration should be given to the temporary opening of sealed panels for the deployment of geophones. These panels could be sealed again after installation. The geophones would need to be installed in such a way as to protect both the transducer and transmission system. The preferred transmission system is by armoured cable in order to maintain operation of the transducers despite closure of the roadways. Even, if the decision is taken

not to temporarily re-open panels, geophones need to be installed as mining proceeds, with stations being established prior to the sealing of panels. Due to the susceptibility of the stations to damage by the closure of the road it is necessary to build redundancy into the system, by putting in more geophones than necessary. It is considered important to establish transducer stations in panels 12E and either 8W or 9W, so that there is a capability to monitor Phalen as it approaches the critical 'threshold' depth encountered in the No. 26 colliery.

The transducers which were envisaged for this system are the Sensor SM-6 digital grade geophones. These should be deployed in shallow boreholes in the roof or floor, at a sufficient depth to be outside the zone of stress relief caused by the driving of the roadways.

It will be particularly relevant to monitor the areas of Phalen mine which are under the old pillar edges of the Lingan mine. Kusznir and Farmer (1983) have shown that the superposition of additional abutment stresses from previous higher workings can lead to major rockbursts in lower seams, particularly in areas where the roof is not a strong sandstone. However, the working of a reliever seam beneath and within close proximity to an unworked outburst-prone seam (within 100m), can often be helpful in alleviating the potential for catastrophic failure. If both seams are outburst-prone it is obviously an advantageous mining strategy to mine the lower seam first, as it then acts as a reliever seam for the upper. However if the upper seam, as in the case of Lingan, is taken first then it appears to concentrate stress into particular areas in the lower seam, particularly beneath pillar or panel edges, which could lead to the potentially higher risk of outbursts in Phalen.

As it has already been suggested, armoured coaxial cabling should be used to transmit the microseismic signals, at least from the sensor deployed in the panel to the haulage roads. It should be realised that damage to the cable is a very real possibility, with an associated loss of information, as a consequence of the inability to maintain the system. Once the signals have been transmitted to the haulage roads, they can be telemetered to the surface by either using standard cabling or fibre optic cables. There is a cost advantage in cabling the signals to a central location in one of the cross cuts between the haulage roads, which could be the site of a multiplexer and modulator. Multiplexed and pulse code modulated signals could then be telemetered to the surface along a single cable or fibre optic link, as opposed to one cable per transducer. With PCM telemetry utilising standard cable, repeater units would be required every 1.2km. The advantage of this system is that it utilises relatively inexpensive and proven technology. However, telemetry could be accomplished with the use of fibre optic links. A cost comparison between standard electrical cable and the fibre optic equivalent has been conducted by CANMET/NORANDA and it has been shown to be economically competitive.

Using readily available optical transmitter and receiver modules with a bandwidth of 10Hz - 10MHz, multiplexed signals can be sent down a single cable. High frequency carrier signals chosen within the pass band of the system are modulated by the outputs of the associated geophones, thus multiple signals can be transmitted along one fibre-optic link. Temperature stability would have to be maintained, however, by temperature compensation of the modulation circuits and automatic frequency tracking at the receiver. The use of fibre optic cables has the advantage of being immune to electro-magnetic interference

in an electrically noisy environment. However, the intrinsic safety implications of this choice are at present unclear.

The data telemetred to the surface must be transmitted via an opto-acoustic isolator to prevent any potential dangerous spikes being transmitted to the underground installations. It is essential that once the data has been telemetred from the underground arrays in both Lingan and Phalen it must be processed and recorded at a central monitoring facility established at either of the two mines, with the results being made available to both mines.

4.3.1.2 Surface Processing and Analysis System

We would recommend that the data should be recorded in both digital and analogue form, with analogue data used for retrospective analysis. This data can be a valuable source of additional data, particularly if event triggering is used as some important microseismic events may fail to meet the triggering algorithms threshold level. Such recording can be accomplished using multi-channel PCM recording on a VCR based recorder. We recommend the new EARTHDATA EDR 128 Series of Instrumentation Tape Recorders, which can record up to 32 channels with a band width of 1.25kHz, and the capability to record up to 128 channels, the cost of a 64 channel unit is of the order of $34000. The latest variation of this recorder is a multideck model allowing for an extended recording capability.

The EDR 128 records signals using Pulse Code Modulation (PCM) as a digital bitstream, incorporating robust error detection and correction systems. The state-of-the-art signal processing electronics allows for the recording and

replay of up to 128 separate analogue signals. If required, the recorded digital data can be transferred directly to a computer for subsequent analysis. The EDR 128 using relatively noise free PCM recording can operate through a wider dynamic range than the traditional FM recorders. The total signal bandwidth of the system being dependent upon digitization rate, number of modules and the number of analogue signals to be recorded.

Digital event storage and analysis can be accomplished on either a UNIX based graphics workstation such as a SUN SPARC or preferably a MASSCOMP DN5450 real time signal analysis workstation with LABWORKBENCH software. This has the ability, with a vector accelerator, to act as a sophisticated event detector, having the ability to digitize and capture whole waveforms and perform real time FFT's on 16 channels of 1kHz bandwidth data. Our extensive experience with such systems leads us to believe that the DN5450 or a later model would provide the ideal computing environment for seismic data analysis and discrimination. Another alternative would be to use one of the extremely powerful micro-computers based around the 25MHz Intel 80486 micro-processor. These would offer the familiarity associated with personal computers, an excellent range of specialist and general purpose software and relatively inexpensive maintenance. The Intel 4000 (i486) series or a Compaq 486/25, with at least 8 Mbytes of RAM and a 348 Mbyte hard disc would offer viable solutions, although the preferred choice would be the Masscomp.

4.3.2 Detailed Panel-based Monitoring

When levels of activity, as measured, on the mine-wide system rise to levels which are indicative of the onset of outburst-prone conditions, we envisage the rapid

deployment of a detailed microseismic/acoustic emission system around the panel, with closely spaced geophones in both single, biaxial and triaxial package configurations.

In this design we have assumed that Retreat Longwall Mining will be the preferred operational method for winning coal and if advance longwall or indeed any other mining strategies are implemented there will certainly be implications for the system and some modifications, particularly to the acquisition geometry, will certainly be necessary.

After an exhaustive consideration of the many systems which have been implemented worldwide for microseismic/acoustic-emission monitoring in both hard-rock and coal mines we feel that the most practicable system in terms of:-

* Intrinsic safety
* Technological advancement
* Commercial availability

is the MESAS (Mine Environment Seismo-Acoustic System) which has been developed by Westfalische Bergwerkschaftkasse (WBK) of Bochum, Federal Republic of Germany as described by Will (1989), or a system with similar specifications which could be synthesised from available component modules. However it should be borne in mind that a clone, look-alike system would certainly not meet the same certifications for intrinsic safety as the WBK system and in fact it is likely that re-certification of the equipment, both the MESAS or a clone system, by CANMET may be necessary.

This system is based around the SEAMEX 87 In-Seam seismic reflection acquisition system which has been commercially

available for some time and has been purchased by the British Coal Corporation as a replacement for the SERCELL system which could only be operated in flameproof enclosures under Letters of No Objection from the Health and Safety Inspectorate.

4.3.2.1 Underground Acquisition System

Block diagrams of the whole system and its component modules are shown in Figures 3, 4, and 5. The transducers which are presently utilised are Sensor SM-6 4.5 Hz digital-grade geophones deployed in shallow horizontal boreholes in mid-seam, the maximum amplitude plane for the propagation of Evison waves, at sufficient depth to be outside the zone of stress release caused by the driving of the roadways, (probably 5 metres). They should be deployed, in such a manner as to facilitate their removal for redeployment elsewhere as the face retreats, with the appropriate sensor planting tool and locking system. The cable should be armoured coaxial cable as dinting and other road maintenance programmes rapidly render standard coaxial cable unusable. To prevent shearing of the cable within the hole it is possible to sheath it in additional hydraulic hose or similar protection. However it should be recognised that the loss of geophones is a very real possibility, despite these precautions, and to some extent they should be considered as consumable items.

4.3.2.2 Geophone Layout

Because of the extremely long length of some of the proposed faces, up to 2.6 Km., giving a very large aspect ratio to the acquisition geometry, it is considered that the system should consist of a minimum of 32 channels and preferably 64 channels, as this would allow the use of 10 triaxial sets and 34 single component instruments. On a

panel of this length, this would give a geophone spacing of the order of 120 metres, based on the instrumentation of Panel 12E, (Figure 6) or if a shorter Panel such as 9W was to be monitored then either a significantly closer geophone spacing could be used, or less stations might be deployed. With such detailed monitoring, it is possible to construct 'event density' maps for the whole panel mine, (see example Figure 7 (top)) and also the locations of destressing blasting, (see example Figure 7 (bottom)) where high stresses were indicated. This does not necessarily imply that destressing blasting should be used, but illustrate the effectiveness of the geophone layout in accurate source locations, particularly as it is known that blasting triggered outbursts in the No. 26 colliery. Specialised destressing blasting was, however, used at Cynheidre Colliery, South Wales, UK, to great effect.

If more than a single face was giving preliminary indications that instability was occurring then this system could be divided into 4 x 16-channels sub-systems which could be installed in separate panels. We do not believe that this would be too sparse a network to adequately monitor a face, as the bulk of the mining-induced seismicity is concentrated in a zone within about 50 metres of the working face associated with the front abutment stresses (Figure 8), although if extraction rates were high it might be necessary to re-deploy the geophones at more frequent intervals.

An outstation consists of four individual geophones which could comprise either 4 single component geophones, 2 biaxial horizontal component packages of 1 three-component (1 vertical and 2 horizontal components) package and a single-component geophone. These enter a DIVO module, Figure 3 and 4, which:-

i) Checks the geophone status
ii) Amplifies and conditions the signal
iii) Lowpass filters the data at 1kHz (anti-alias filter)
iv) Digitises the signal with a 14 bit (16 including gain bits) A/D and multiplexes the signals
v) An onboard CPU controls the processes and the data is then multiplexed and Pulse Code Modulated for telemetry to the main underground control unit. This reduces installation and maintenance costs.

Telemetry of signals from the DIVO units to the central Master Unit is presently accomplished by standard cabling with PCM repeater units every 1.2km. This has the advantage of using cheap and tested technology. However, this could also be accomplished using fibre-optic links which has the advantage, in an electrically noisy environment, of being immune to electro-magnetic interference. Bandwidths of 10Hz to 10MHz are easily obtainable with currently available technology permitting the multiplexing of many channels within a single fibre.

Eight DIVO units (32 channels) can be connected to the underground control unit which consists of a channel selection module which de-multiplexes the signals and chooses 16 out of the 32 available channels. These then become slave processes in which data are filtered and buffered, (Figure 5) under the control of a master processor.

All the data are then re-multiplexed and telemetred to the surface over a single cable via an opto-acoustic isolator to prevent any potentially dangerous spikes being transmitted to the underground installations.

4.3.2.3 Surface Processing and Analysis System

At the present time, the processing system is based around a MicroVax II computer with an attached 6250 BPI Tape recorder. However, the rapid change which is taking place in the workstation market leads us to recommend that the final computer should be a UNIX-based graphics workstation either a SUN SPARC or preferably a MASSCOMP DN5450 real-time signal analysis workstation with LABWORKBENCH software. This can, with a vector accelerator, act as a sophisticated event detector, having the ability to capture whole waveforms and even perform real-time FFT's on 16-channels of 1 kHz bandwidth data and our extensive experience with these machines leads us to believe that they or even a later model would provide almost the ideal computing environment for seismic data analysis and discrimination.

Another alternative would be to use one of the extremely powerful microcomputers based around the 25 MHz Intel 80486 microprocessor as these offer significant processing power, the familiarity associated with personal computers, an excellent range of specialist and general purpose software and relatively inexpensive maintenance which may be an important factor and advantages of such an option. The Intel 4000 (i486) series or a Compaq 486/25 both with at least 8 Mbytes of RAM and 348 Mbyte hard discs would offer viable solutions.

In addition to event storage and analysis in digital form we would recommend that the data be also recorded in analogue form for retrospective analysis as a continuous data set. This can be a very valuable source of additional data particularly in the event of an incident or inquiry. This can be accomplished using multi-channel PCM recording on a VCR based recorder. A particularly

appropriate model would be the new EARTHDATA EDR 128 Series of Instrumentation Tape recorders which can record up to 32 channels with a bandwidth of 1.25 kHz, described in Section 4.3.1.2.

4.3.2.4 Channel-Wave Seismology

The implications of making measurements of seismic events, from within the coal with detectors which are themselves within the coal, should not be underestimated. Coal has a low density and a low seismic velocity with respect to the floor and roof rocks and the product of density and velocity, which is the Acoustic Impedance is sometimes 4 times less than that of the neighbouring strata. A point source within the seam will generate waves which are reflected at both boundaries of the seam and for rays with low angles of incidence Total Internal Reflection will occur, leading to a guided or channel wave which will propagate along the seam.

Two possible modes of propagation can be observed, SH or Evison waves are horizontally polarised and are the principal mode of interest, but P-SV waves, which are also known as Krey waves do exist with vertical planes of polarisation. These are the Normal-Modes of oscillation of the seam. Both theoretical and observational studies of this mode of propagation show that it is strongly dispersive, ie. different frequencies within the wave travel at different velocities leading to a considerable spreading out of the seismic pulse which increases with increasing distance. Figure 9 shows the dispersion analyses of 20 events for the first Love mode (Love wavws are characterised by horizontal motion perpendicular to the direction of propagation with no vertical motion. The amplitude of the SH wave is at a maximum at the centre of the seam and decreases vertically with the principal

energy confined to the seam, although, depending on the frequency of the waves, some disturbance of the surrounding strata does occur. Refracted head waves, which propagate along the interface between the coal and the surrounding materials, are also present and often constitute the first arrival of energy on a seam detector, because they propagate at the velocity of the fastest material. Normal P and S-V waves do not exist in a coal seam as they contravene the boundary conditions imposed by the physical nature of the coal sandwich. The diffuse nature of the channel wave onset does not facilitate the use of first arrival times for the location of seismic events in the way which is commonly implemented in normal microseismic monitoring and event location requires careful consideration and sophisticated pre-processing of the data and, in fact, workers who have tried simplistically to implement normal least squares solution methods for Channel-waves have experienced little success. Likewise, simply using the differential p and s wave travel times to determine hypocentral distances is suspect, as different frequencies within the s-wave in particular will travel at different velocities.

There is, however, one major advantage with channel waves; it is known that the hypocentre must lie within the seam and the problem therefore reduces to a two-dimensional solution.

Figure 10 shows a typical channel wave from a natural micro-earthquake which was recorded from a horizontal component geophone which formed part of a multi-component borehole sonde situated some 500 metres in advance of a working face. It shows a very small refracted p first arrival followed by a relatively clear low-frequency SH arrival at 0.1 seconds and with a very distinctive and strong high-frequency SH arrival seen at 0.3 seconds.

This is the AIRY phase and occurs at the minimum velocity on the dispersion curve which in fact can be deduced from data of this kind if the location of the source is known, as would be the case if the event was a shot-firing instead of a naturally-occurring seismic event. The left hand set of curves shows the signal after passing it through successive narrow band filters with the centre-frequency of the filter on the left. This type of plot clearly shows that different parts of the frequency spectrum of the signal are arriving at different times with the Airy phases at around 260 Hz arriving last.

An alternative display of the same information is given in the right hand plot; here a variable-area display of the Hilbert Transform of the data, which closely defines the shape of the envelope of the signal, is used instead of the signal itself. If we choose a particular frequency at which both p and s-waves can be seen, we can measure the separation between the maximum of the Hilbert transform and if we know the phase velocities for that frequency we can estimate the distance to the hypocentre. Distances derived in this way, from a set of geophones can now be used in a least-squares or SIMPLEX optimisation algorithm to locate the event with a good deal of confidence.

A much more elegant solution is available, however, if biaxial or triaxial component data have been recorded as it is possible to reconstitute the true particle motions on a horizontal plane by plotting the two horizontal components against one another in the form of a hodogram (similar to Lissajous figures in Electrical Engineering). The first particle motions of the low-frequency p-wave will be, by definition for a compressional wave, along the line of propagation. This then defines the azimuth of the event and if the range of the event is now known, the hypocentre can be plotted from a single geophone package.

Obviously, having additional information from several geophones will give a statistically better estimate of the event position.

The implications for the software of this discussion are obvious; general purpose microseismic algorithms are not suitable and specialised algorithms must be used. Additionally, seams in a new mine or new seams in the same mine must have their dispersion relations established using a transmission survey so that the variation of velocity with frequency is known.

5. CONCLUSIONS AND RECOMMENDATIONS

A review of microseismic monitoring systems which have been developed and deployed worldwide to monitor the mine environment has revealed that the majority the systems have been deployed as research tools and have either been assembled by the groups themselves or alternatively assembled on an ad hoc basis to fit the requirements of the monitoring programme. It would seem likely that this approach, the 'construction' of a system from off the shelf components would be the preferred method of proceeding in the establishment of a monitoring system for the Sydney Coalfield.

The review of the systems has shown that those developed in Canada have mainly been applied to hard rock, and evaporite mines, with other hard rock applications having been identified from the USA, Sweden, Australia and India with some reference to systems in Eastern Europe. With coal mining applications being identified from the USA, the UK, Germany, France, Australia, Japan, China, the USSR, Czechoslovakia, Poland and Hungary.

Of the available systems most were limited either by a perceived inadequate number of channels, or the bandwidth and sampling rates or both. The Electro-Lab system provided source location information but does not have the ability to store full waveform data, as it stands; and does not have a predictive capability, nor it would appear the ability to process channels waves which require specialised software. The MESAS system, however, is known to have been designed specifically for in-seam monitoring and has the required software for the application. A similar system based on this could be constructed.

Of the systems identified for coal mining applications, many have relevant features applicable to the design and

development of a system for the Sydney Coalfield. Many of these systems have been successful in recording activity associated with outburst conditions and one system in particular, from the UK, was used as a management tool and it is believed to be the first such system to control a colliery.

Of those developed for coal mining, some have features of relevance to the design of a system for the Sydney Coalfield. The system developed for the Provence coalfield, France, described by Revalor et. al., (in press) was based around two systems, one a panel based system and the other a larger network to monitor the mine as a whole. It is considered that this represents an ideal methodology, although the system itself is limited by both the number of stations and bandwidth.

In Australia, accelerometers have been installed in the coal rib (McKavanagh and Enever, 1980) and whilst the system is unlikely to be used as it was a single channel system, it shows the applicability of installing transducers at seam level.

In Japan, the Sunagawa mine used a combined surface and underground system, (Sato and Fujii, 1987), producing a 3D system to monitor the whole and this is considered relevant to the overall design. Panel based systems such as those deployed in Horonai (Sato et. al., 1980) and Miike, (Kaneko et. al., (in press) an undersea mine experiencing pure coal bursts, should also be considered to form part of the overall system developed for the Sydney Coalfield.

In West Germany, the MESAS system has been specifically designed for coal mining applications as a panel based system with the necessary software to process dispersed channel waves. It is a digital PCM system which features

full waveform acquisition and processing, and this represents one of the most applicable system to monitoring part of the mine. Whilst this system could be used in the Sydney Coalfield to monitor individual panels, we believe it to represent a considerable cost, however, it should be possible to construct a similar system from off the shelf components. It is likely that both the MESAS system and also a clone would require certification for intrinsic safety.

Of the systems developed in the USA, Leighton and Stebley (1975) describe a dual frequency system, deployed in Coal Mines of Western Colorado, the high frequency element would, however, only be useful for monitoring in specific locations as it would be effective over a limited range, but it has the advantage of being insensitive to man-made noise.

At Cynheidre Colliery in the UK, a surface microseismic monitoring system was deployed to monitor the mine environment. Although limited to a surface disposition it was used successfully as an aid to management in controlling the operation of the mine. This system in conjunction with special destressing techniques and a Code of Practice is believed to have enabled the mine to operate for four years without the occurrence of an outburst and manage successfully several serious gas emission incidents, initially flagged by the microseismic monitoring systems. Although a purely surface system, this should not preclude the application of techniques and knowledge gained from this project.

Many of the systems reviewed were based around a 3D approach with an element monitoring the whole mine environment, often deployed on the surface and/or deployed throughout the workings, with element designed to monitor smaller localised areas. This approach has been used as

far as possible in this design. Based on the surface seismic work carried out for example Styles et. al., (1987a, 1987b, 1988, 1990) enough energy reaches the surface, consequently a surface element is justified. The deployment of geophones within the seam is justified by the knowledge that acoustic emissions generated by fracturing in the vicinity of the coal seam will couple into the seam as a guided channel waves. The usefulness of this deployment position is substantiated by our experience with monitoring in boreholes in advance of faces which showed the ability to detect events at considerable distances and also the installation of accelerometers in the coal rib in Australian systems. It is also important that the system should have a broad bandwidth, with the capability of monitoring in the low frequency part of the spectrum, as low frequency emergent events have been useful indicators of mine stability in hard-rock mines (Gibbons, 1980), Potash mines (Wong, 1984) and in coal mines (Styles et. al., 1987a, 1987b, 1988, 1990).

The use of tomographic imaging may also be of use as it is known that the outbursts experienced in the No. 26 Colliery were associated with palaeo-fluviatile channel sandstones. Although difficult to ascertain their three dimensional disposition by drilling, their positions could be inferred from tomographic images. Such a channel sandstone, even if it does not cut down into the seam could, in theory, be detected by such techniques, as its presence could cause a differing stress distribution which would in-turn affect the velocity structure within the seam and it is this velocity structure, although in terms of slowness, which is mapped in such a technique.

It is recommended, therefore, that a microseismic monitoring system for coal and gas outbursts should be composed of three elements.

1) **A Surface Seismograph Network**
Tri-axial sensors in quiet environments to provide three-dimensional control for hypocentral locations and discriminate events occurring above the level of the coal seam

2) **A Mine-Wide Underground Microseismic System**
Geophone spacing of the order of 1 km to recognise the onset of anomalous seismic activity in a particular area

3) **Local detailed microseismic system**
Geophone spacings of 10-20 metres to give accurate locations of 5-10 metres and the localisation of event energy contours in order to identify potential outburst zones with elements 1 and 2 forming a mine wide monitoring system.

In developing a detailed methodology to fulfill the requirements of CANMET and CBDC a 'two pronged' approach has been adopted. We would recommend for a microseismic monitoring system for the Lingan and Phalen mines that:-

1) the two mines should be treated as one integrated microseismic system for monitoring purposes to maximise the three dimensionality.

2) a mine wide system should be deployed, with a 'surface' element of either 5 ocean bottom seismometers deployed in a cross array to cover the whole colliery take; or alternatively geophones deployed in boreholes drilled up from the Lingan workings; and an underground array of triaxial geophone sets deployed in bothmines with spacings of the order 700-800 metres, which equates approximately to every 3 to 4 panels

down dip, 3 in order to delineate areas which are developing an outburst risk.

3) when conditions dictate a detailed panel based system should be deployed with a minimum of 32 geophones arranged as bi-axial sets, to allow for a location accuracy of the order of 2 metres parallel to the face and approximately 5 metres perpendicular to the face together with energy density plots.

The system should be capable of recording and capturing full waveform data for both on-line and off-line processing and it should provide:-

- the location of areas of high microseismic activity and to indicate zones of high stress
- the ability to investigate the mechanisms of outbursts
- discrimination of the onset of abnormal activity
- real time information to Colliery Management to allow decisions to be taken as to
  - face advance rates
  - face halts
  - possible implementation of firing
  - resumption of cutting after incidents
- confidence to mine personnel and reduce psychological stress

It is envisaged with the use of such a system it would be possible to keep mine workers and supervisors informed about the locations of abnormally high event rates, which could be inspected and treated with greater caution and if destressing and/or drainage techniques are to be used these could be implemented. Which should increase the confidence of personnel and reduce the psychological stress on those at risk. It is also hoped that during the

operation of the system precursors to outbursts would be determined and predictive capabilities could be built into the system. In the event of false alarms, in which outburst conditions are predicted which do not culminate in an outburst, it has been found in the UK that neither confidence nor credibility has been lost, as the issued warning has generally been caused by an abnormal situation often requiring the implementation of additional safety measures. Also if a predictive systems is operating and interpreted correctly, it is anticipated that once an alarm has been issued the potential outburst will not develop into a catastrophic failure but should be released in a controlled manner.

A phased approach would be recommended for the implementation of the system:-

1) **A Field Test**
   Which should determine the frequency and amplitude range of the anticipated microseismicity so that appropriate transducers may be selected.

2) **Generation of a Velocity Model**
   A realistic seismic velocity model must be constructed for the mine environment and also the coal seam, as the location accuracy of the system is strongly dependent upon this model.

3) **A Pilot Study**
   Which should address the choice between deploying an OBS 'surface' element, with buoys maintained on station, or an alternative of deploying geophones in boreholes drilled into areas above the Lingan workings. All other elements of the system should also be tested during this phase, which should lead to the

final stages of deployment.

4) **The Deployment of the Full System**
During which events should be routinely located, source mechanisms should be determined, events classified and precursory patterns determined.

During the Pilot Study invaluable data could be accumulated and events classified by type; which should assist in the design of 'intelligent' trigger systems, which could use the techniques of feature extraction and pattern recognition. Which may eventually result in the decision to discontinue continuous recording in the final commissioned system assuming that their is confidence is assured that all pertinent events are recorded by a triggered recording system. However, it is essential in the initial stages that continuous recording of the incoming data is undertaken for a full and detailed analysis, and it must be appreciated that additional equipment may be required to monitor the recorded data and produce hard copy output for later off-line processing. It is hoped that microseismic precursors would be determined for later implementation as a predictive system to forwarn of outburst prone conditions and allow for the panel based system to be deployed. It would be assumed that the majority of the panel based system would be in place awaiting the rapid deployment of the transducers as and when necessary.

for S.J. Emsley

for P. Styles

C.M.K. Yuen, P. Eng. C.M.-k. Yuen

REGISTERED PROFESSIONAL ENGINEER PROVINCE OF ONTARIO

TABLE 1 OUTBURST-PRONE AREAS OF THE WORLD

Country	Area	Worst affected mines	Numbers of outbursts	Gas involved
Australia	Sydney Bowen Basins	Leichhardt (>250) West Cliff (126) Tahmoor (49) Metropolitan (>18) Collinsville (>18) Appin (2) Corrimal	over 500 to 1983	CO_2/CH_4
Belgium	Charleroi-Mons (mines closed in 1970's)		1190 between 1956 and 1963	CH_4
Bulgaria	Balkans		105 to 1974	CH_4
Canada	Alberta/British Columbia (mines abandoned in 1960's		360 to 1932	CH_4
	Nova Scotia	No. 26 mine	37 since 1977	CH_4
China	(widespread)		9845 to 1981	CH_4
Czechoslovakia	Ostrava-Karvina (mines closed in early 1970's)		279 to 1974	CO_2/CH_4
France	Cevennes Basin (mines closed in early 1970's)	Merlebach Lorraine	6245 between 1899 and 1964	CO_2/CH_4
Federal Republic of Germany	Ibbenbueren Ruhr (7 mines affected)	Ibbenbueren (189) Hugo Haard	213 between 1903 and 1982	CH_4
Hungary	Pecs Basis	Mecsek	565 to 1982	CH_4

Golder Associates

TABLE 1 (CONTINUED) OUTBURST-PRONE AREAS OF THE WORLD

Country	Area	Worst affected mines	Numbers of outbursts	Gas involved
Japan	Hokkaido	Yubari Shin Miike Horonai	1000 from 1925 to 1964; 21 from 1970 to 1980	CH_4
Poland	Lower Silesia (44 fatalities)	Nowa Ruda (1295 between 1900 and 1980)	about 2000 (over 1500 between 1900 and 1980)	CO_2/CH_4
UK	West Wales (28 fatalities)	Cynheidre	250 between 1907 and 1981	CH_4
USA	Colorado	Dutch Creek	(a few since mid 1970's)	CH_4
USSR	Donetz Basin (80% of seams outburst-prone) Donbass		3463 between 1960 and 1 Jan 1983	CH_4 $CH_4/CO_2/N_2$
YUGOSLAVIA	Soko Coalfield		Few	

Golder Associates

TABLE 2 STATISTICS OF THE WORST OUTBURSTS

Country	Date	Area	Mine Coal in tonnes	Outburst methane in m^3	Outburst	Fatalities
Australia	13 Oct 54	Bowen Basin State Mine	Collinsville	1,000	14,000	7 (CO_2)
Australia	1 Dec 78	Bowen Basin	Leichhardt	500	12,000	2
Canada	1904	British Columbia	No.1 Morrissey	3,500	140,000	14
FRG	26 Aug 81	Ibbenbueren	Ibbenbueren	750	21,240	8
France	1958		Pontil	210	? (mixed)	7
Hungary	1969		Zobak	1,500	135,000	Yes
Japan	16 Oct 81	Hokkaido	Yaubari Shin	4,000	600,000	93
Poland		Silesia	Nowa Ruda	5,000	800,000	44 CO_2
UK	Nov 71	West Wales	Cynheidre/ Pentremawr	400	60,000	6
USSR	1969	Donbass	Yu.A. Gagarin	14,000	250,000	

Golder Associates

TABLE 3
DISTRIBUTION OF OUTBURSTS IN THE GWENDRAETH VALLEY
TO 1 AUGUST 1986

COLLIERY	OUTBURSTS			TOTAL
	SPONT.	INDUCED	UNCLASSIFIED	
CYNHEIDRE	38	76	-	114
GREAT MOUNTAI	23	13	-	36
PENTREMAWR	10	20	-	30
PONTHENRI	25	1	-	26
PLASBACH	3	-	18	21
CARWAY	4	-	-	4
PONTYBEREM	1	3	-	1
COEDEAN	1	-	-	1
TOTAL	105	113		18236

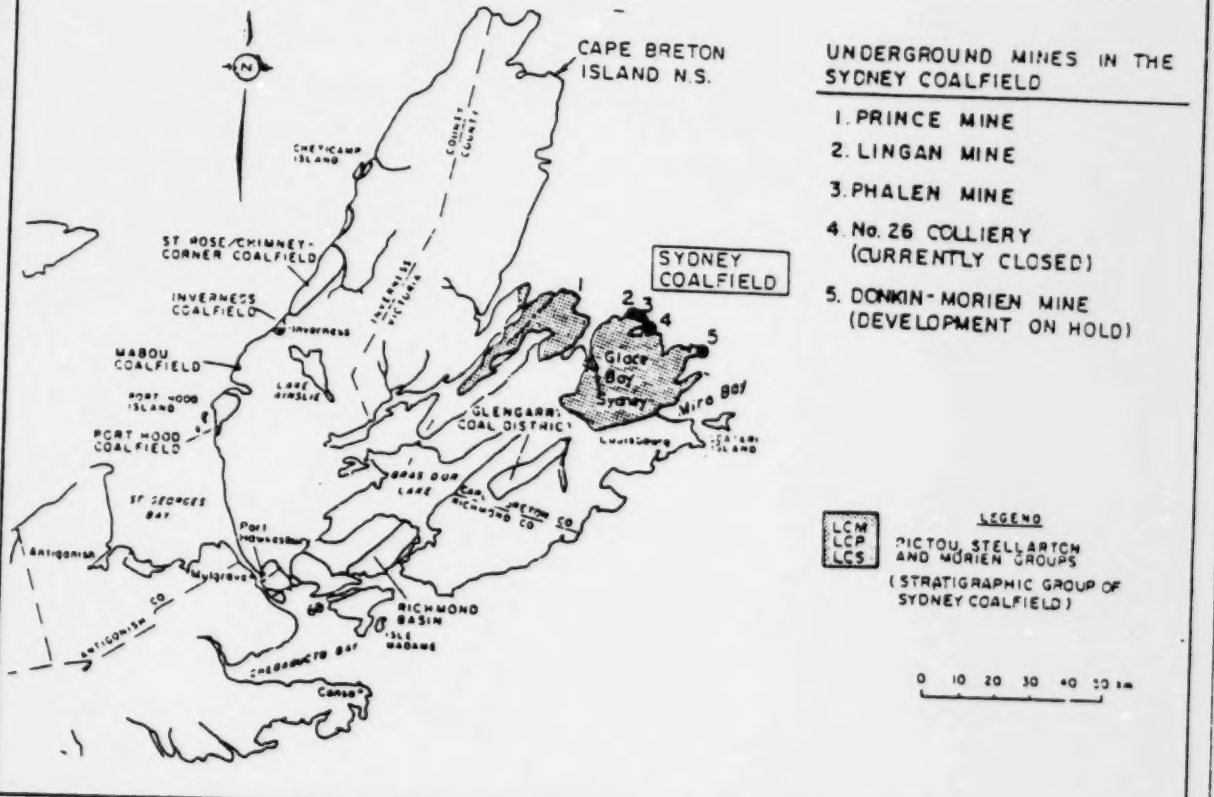
DATE MARCH '90

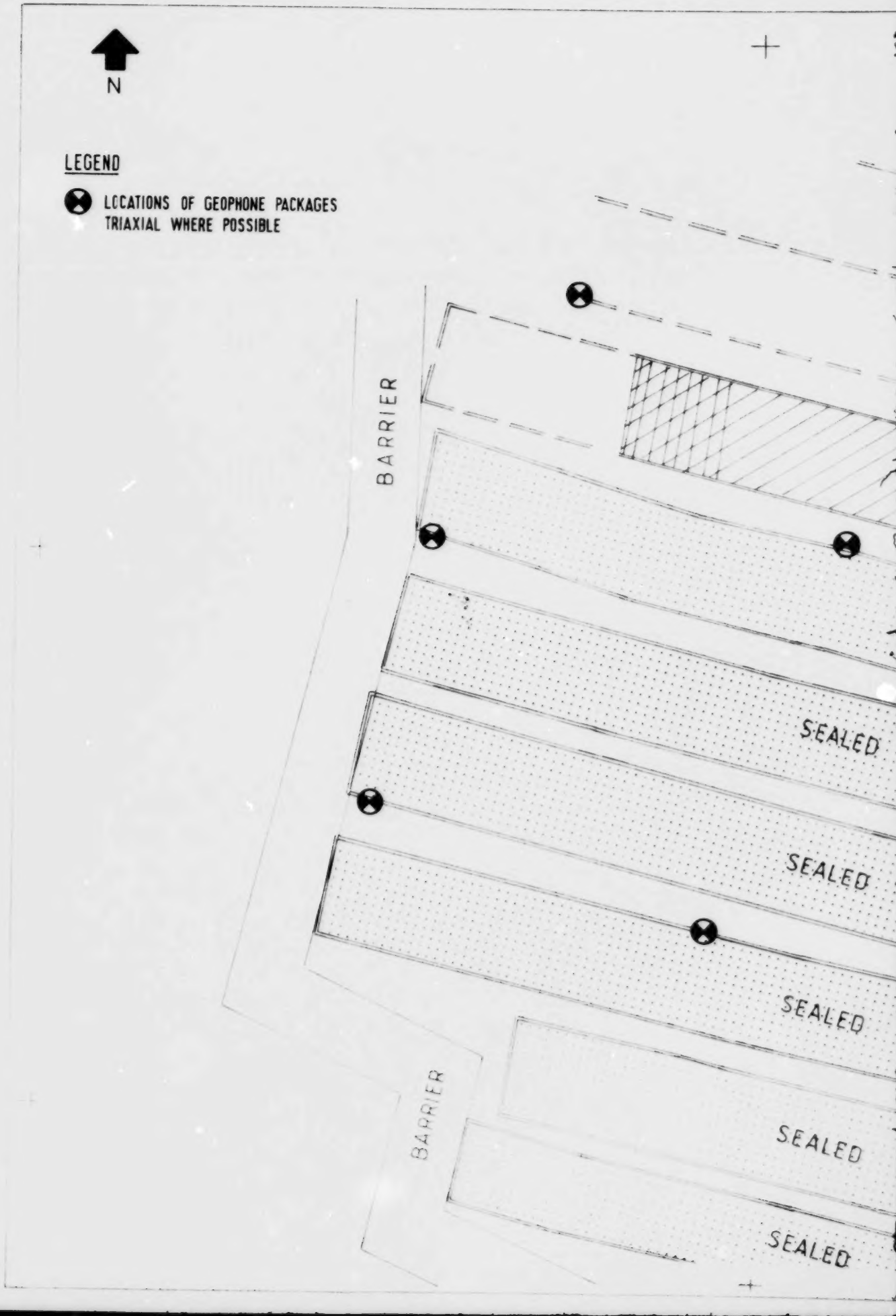
REVIEWED BY

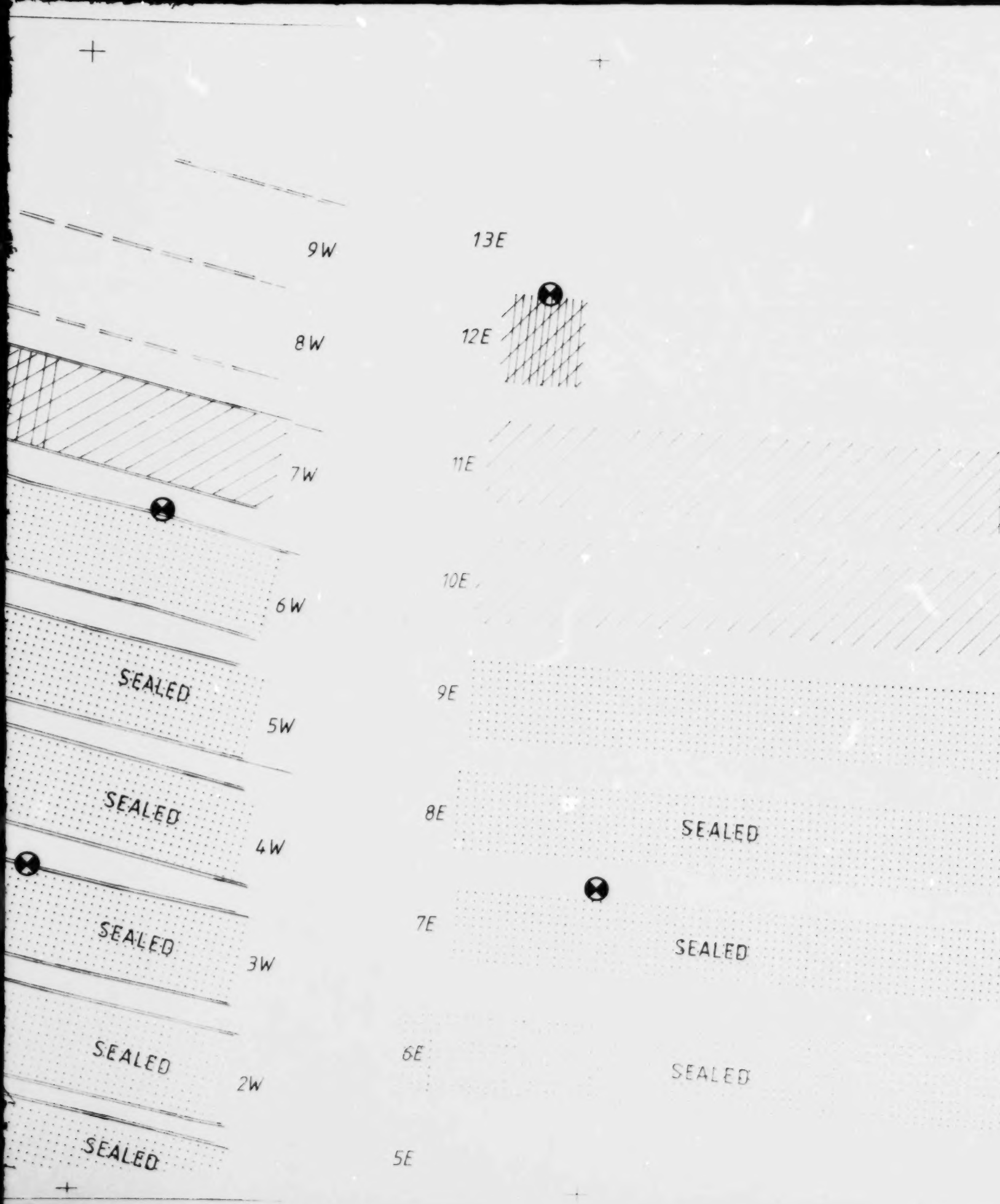
DRG No A 895 1044 (891 - 1736)

LOCATION MAP OF SYDNEY COALFIELD, NOVA SCOTIA

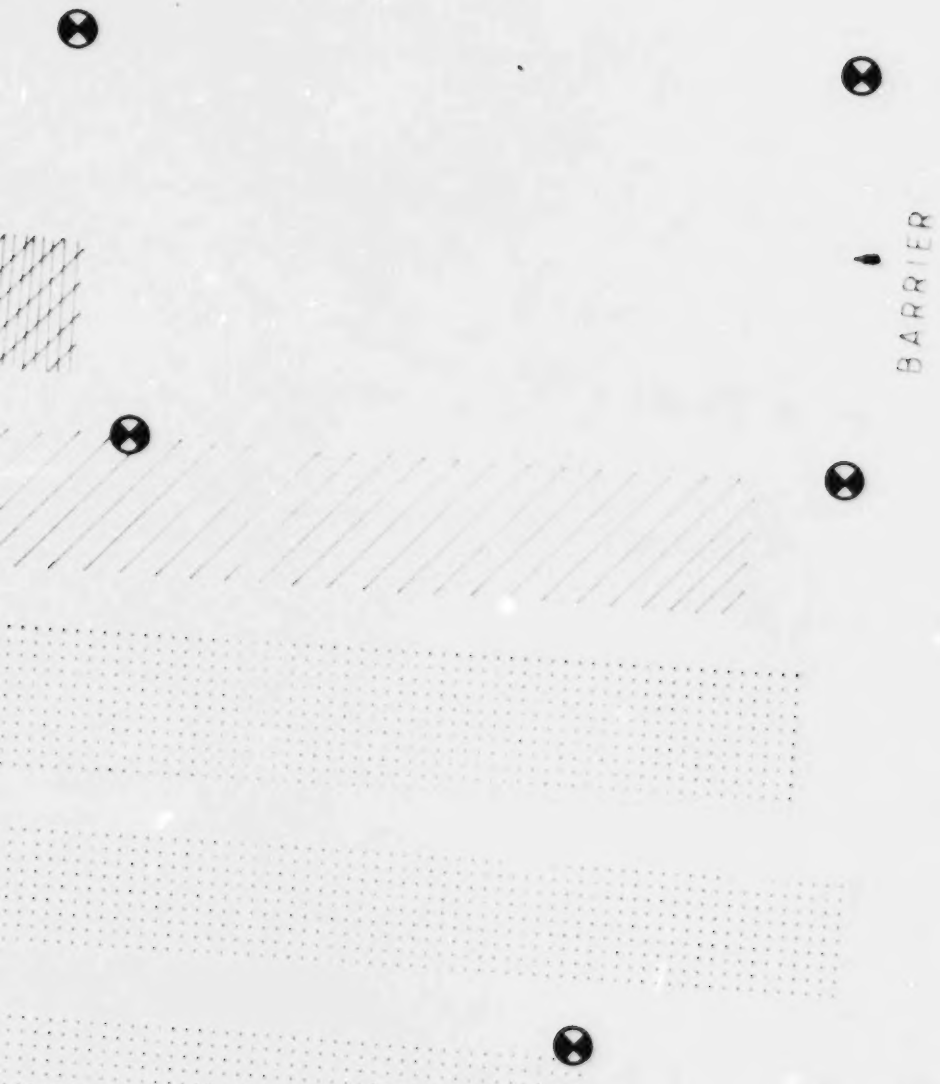
FIG. 1




N
LEGEND
LOCATIONS OF GEOPHONE PACKAGES
TRIAXIAL WHERE POSSIBLE
BARRIER
SEALED
SEALED
SEALED
SEALED
BARRIER
SEALED
SEALED


9W
8W
7W
6W
SEALED
5W
SEALED
4W
SEALED
3W
SEALED
2W
SEALED
13E
12E
11E
10E
9E
8E
SEALED
7E
SEALED
6E
SEALED
5E

POSSIBLE LOCATIONS FOR GEOPHONE PACKAGES FOR LINGAN COLLIERY



SCALE 1 10000

0 100 200 300 400

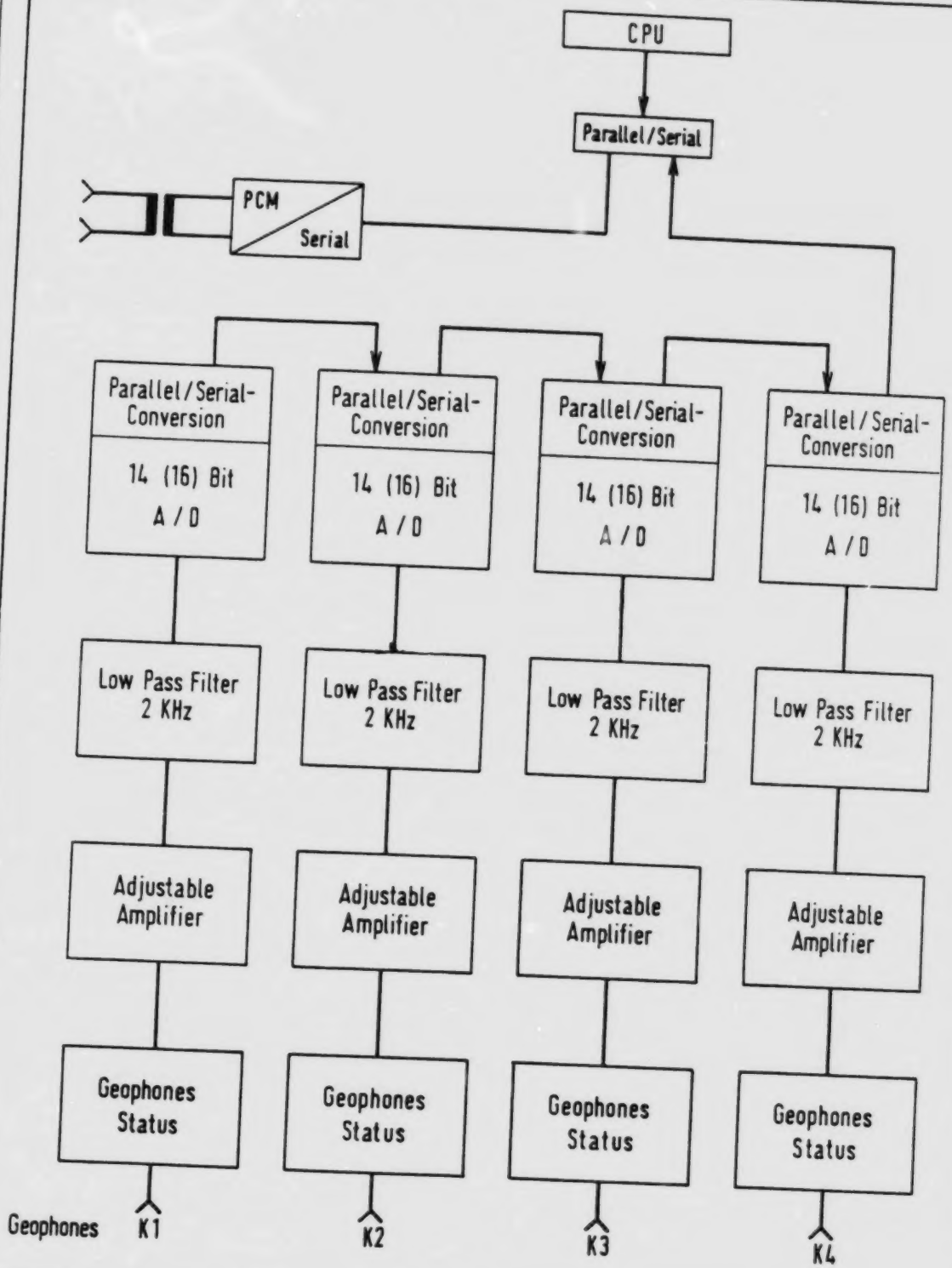
DATE MARCH '90

REVIEWED BY

DRG No A 895 1044 (891 - 1736)

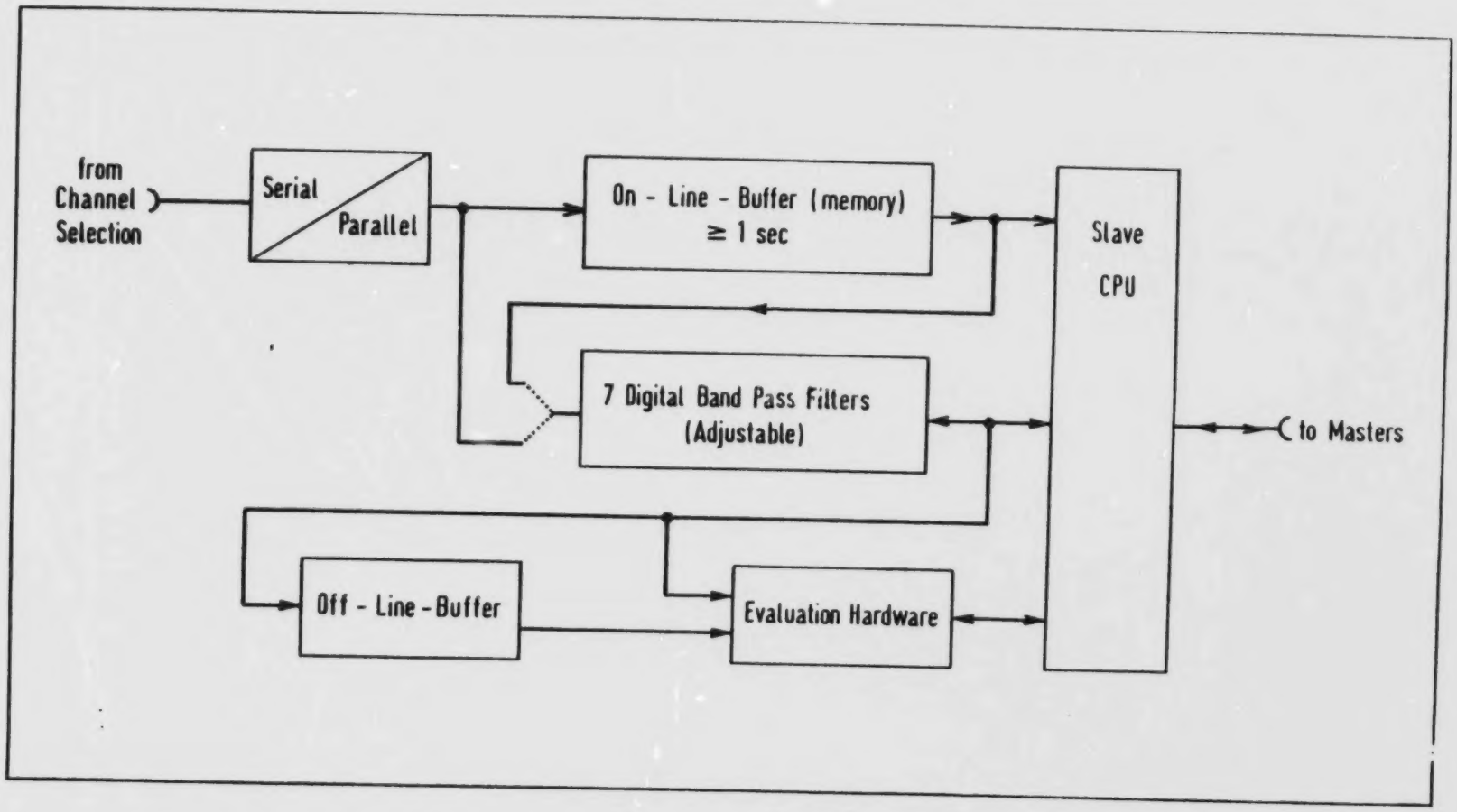
BLOCK DIAGRAM FOR A "DIVO" UNIT, A FOUR CHANNEL ACQUISITION MODULE

FIG. 3



NOTE

Redrawn from Rockburst Prevention with Geophysical Methods, Will M., (1989) Westfälische Berggewerkschaftskasse WBK - Institut Für Geophysik



NOTE
Redrawn from Rockburst Prevention with Geophysical Methods, Will M. (1989)
Westfälische Berggewerkschaftskasse WBK - Institut Für Geophysik

BLOCK DIAGRAM OF A SLAVE UNIT, WHICH RECEIVES DATA FROM THE DIVO UNITS AND APPLIES FILTERS

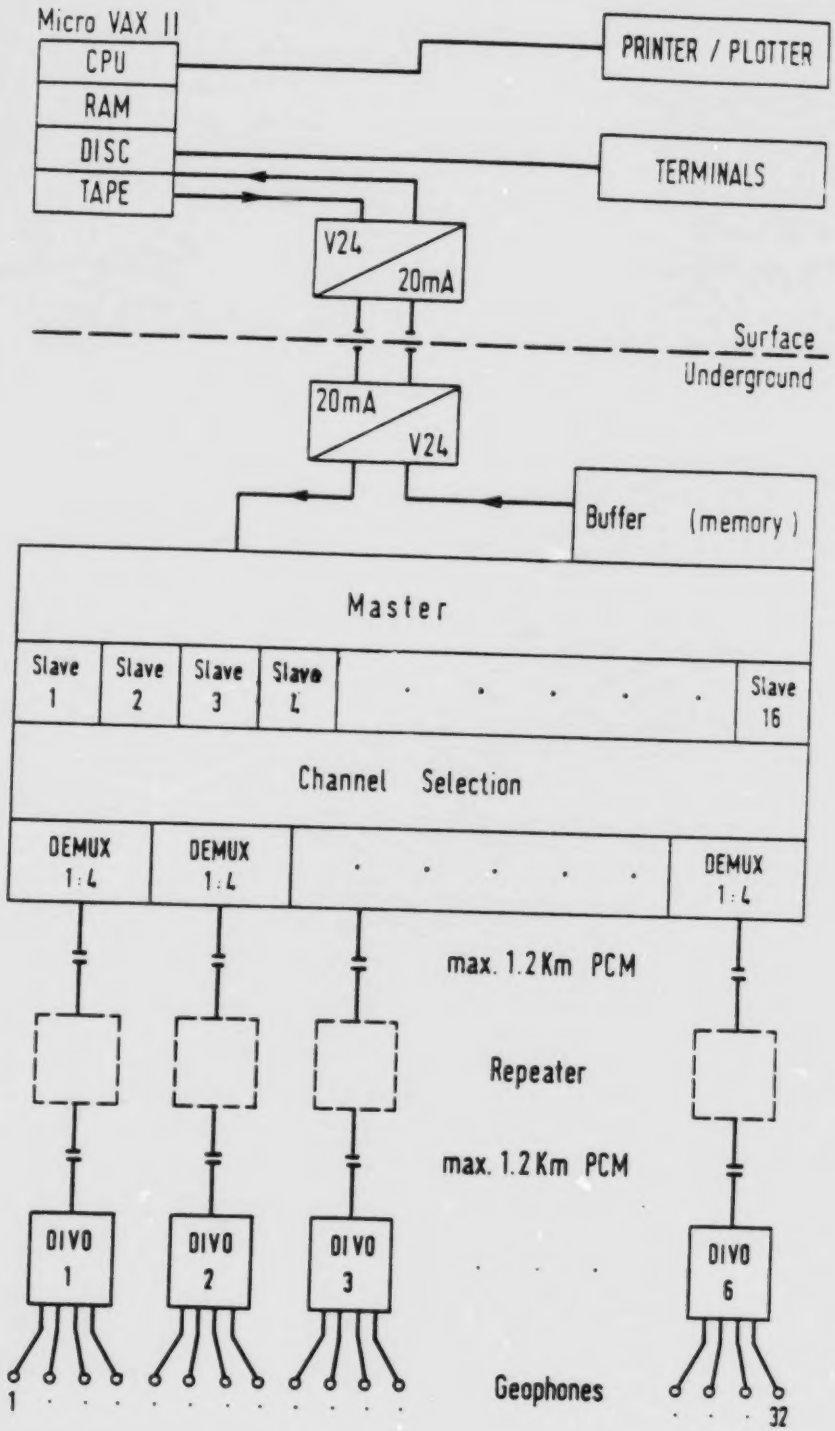
FIG. 4

DATE MARCH '90

REVIEWED BY

BLOCK DIAGRAM OF THE COMPLETE MESAS SEISMOACOUSTIC SYSTEM, SHOWING EQUIPMENT ABOVE AND BELOW THE GROUND

FIG. 5



NOTE

Redrawn from Rockburst Prevention with Geophysical Methods, Will M., (1989) Westfälische Berggewerkschaftskasse WBK – Institut Für Geophysik

DRG No A 895 1044 (891 - 1736)

DATE MARCH '90

REVIEWED BY

DRG. No. B 895 1044 (891 - 1736)

N

E 12000

10W

9W

8W

7W

6W

5W

13E

12E

11E

10E

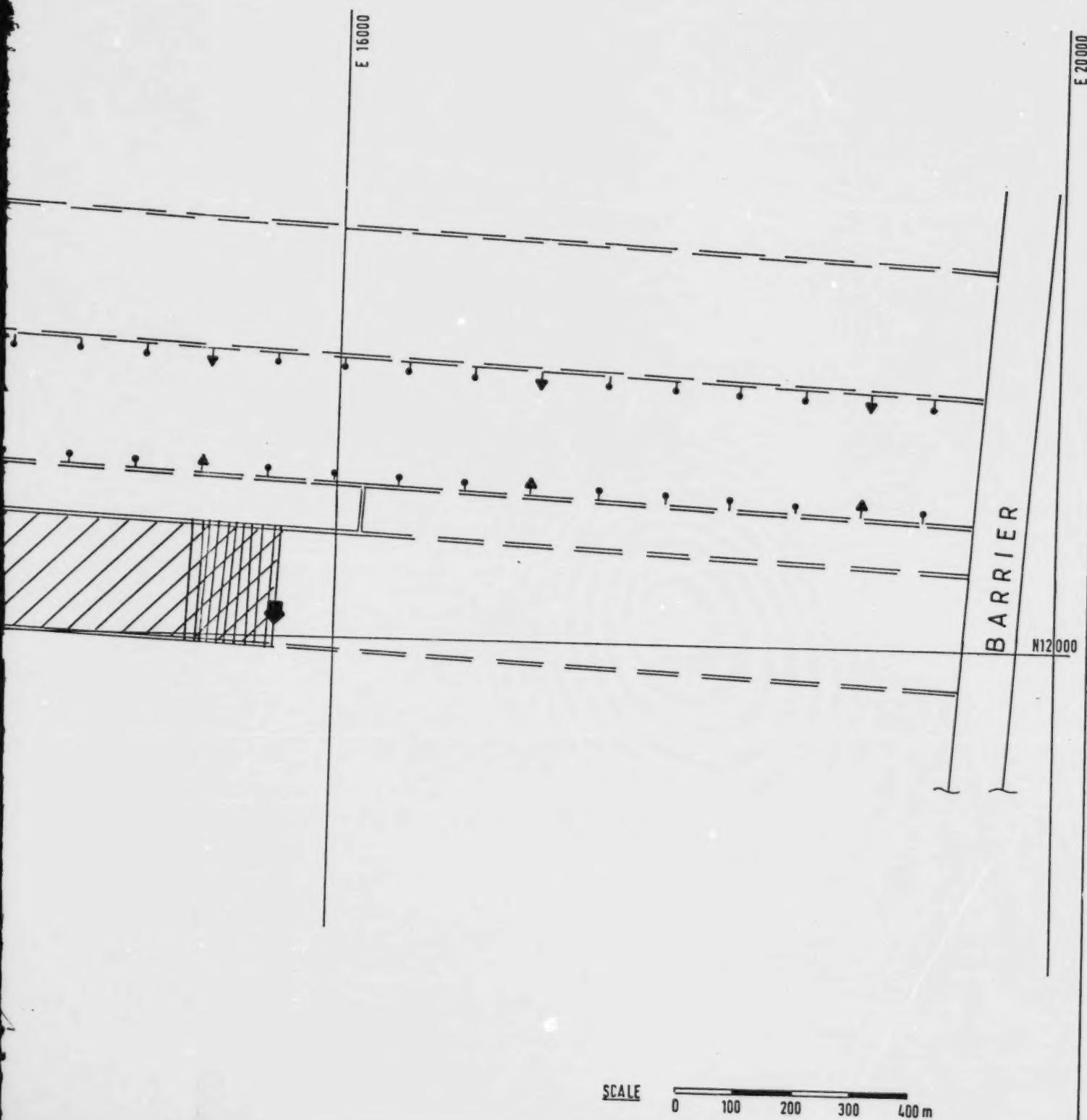
9E

LEGEND

- INTAKE AIR
- RETURN AIR
- TRIAXIAL GEOPHONE SETS
- SINGLE AXIS GEOPHONES

TYPICAL GEOPHONE LAYOUT FOR A DETAILED PANEL BASED MONITORING SYSTEM

FIG. 6

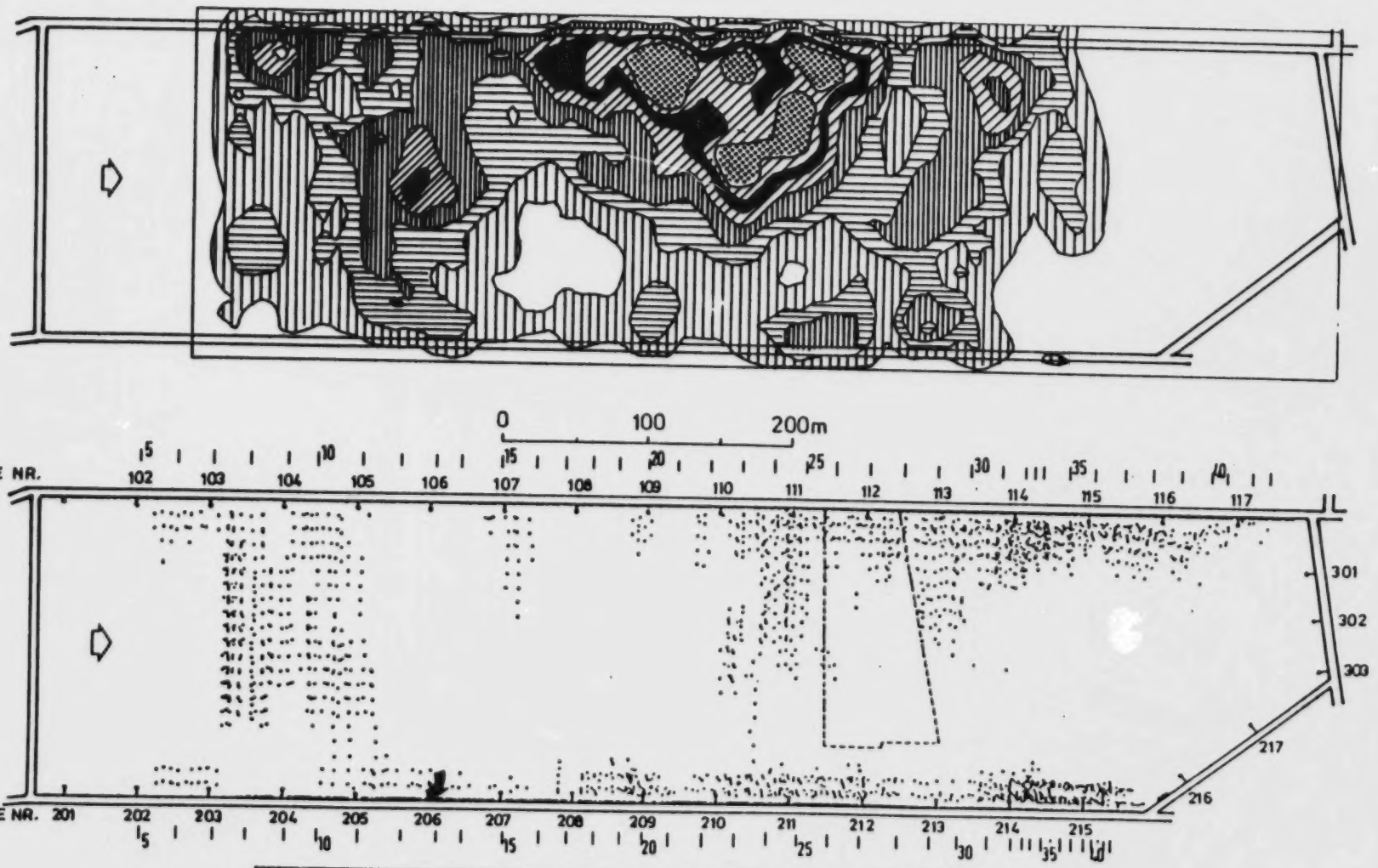


Golder Associates

DRG No A 895 1044 (891 - 1736)

REVIEWED BY _____

DATE _____



NOTE

Redrawn from Rockburst Prevention with Geophysical Methods, Will M., (1989) Westfälische Berggewerkschaftskasse WBK - Institut Für Geophysik

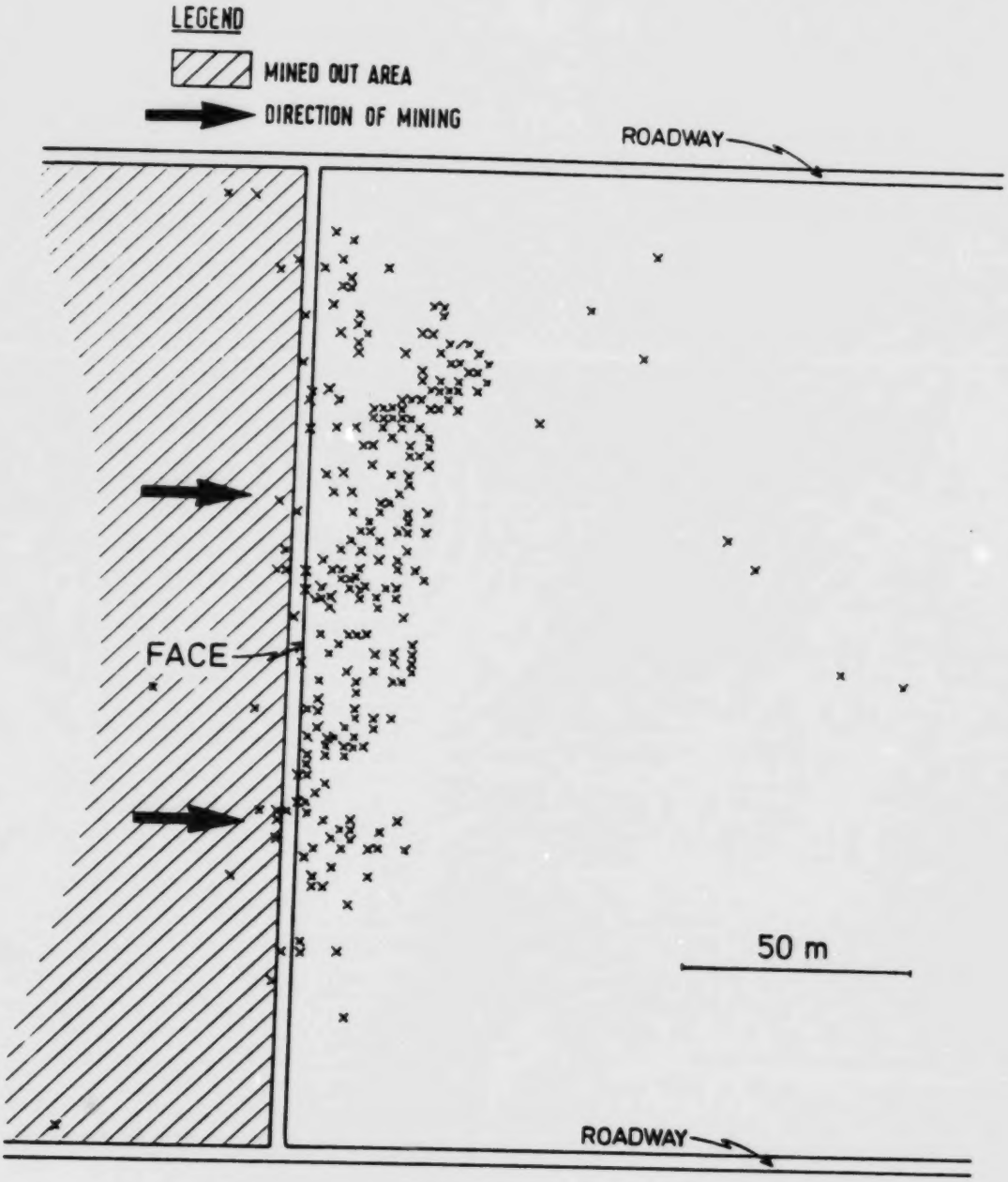
Golder Associates

EVENT DENSITY DIAGRAM AND LOCATIONS OF DESTRESSING BLASTING

FIG. 7

THE SOURCE LOCATIONS OF EVENTS CAUSED BY MINING

FIG. 8



NOTE

Redrawn from Rockburst Prevention with Geophysical Methods, Will M., (1989) Westfälische Berggewerkschaftskasse WBK - Institut Für Geophysik

DRG No A 895 1044 (691 1/36)
DRAWN BY
DATE MAR'90

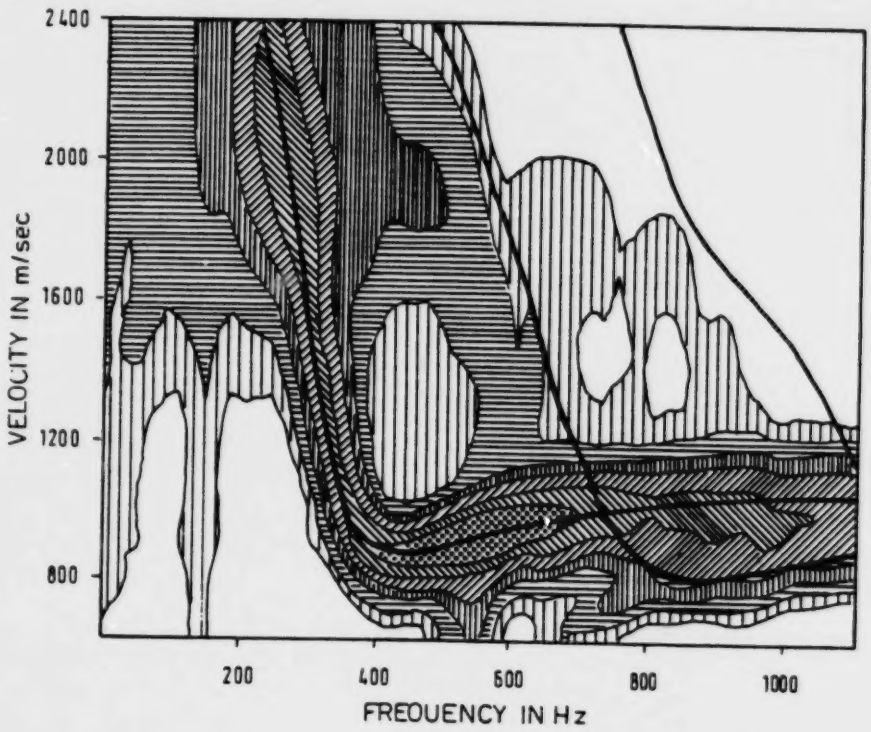
DRG No A 895 1044 (891 - 1736)

DAT MARCH '90

REVISED BY

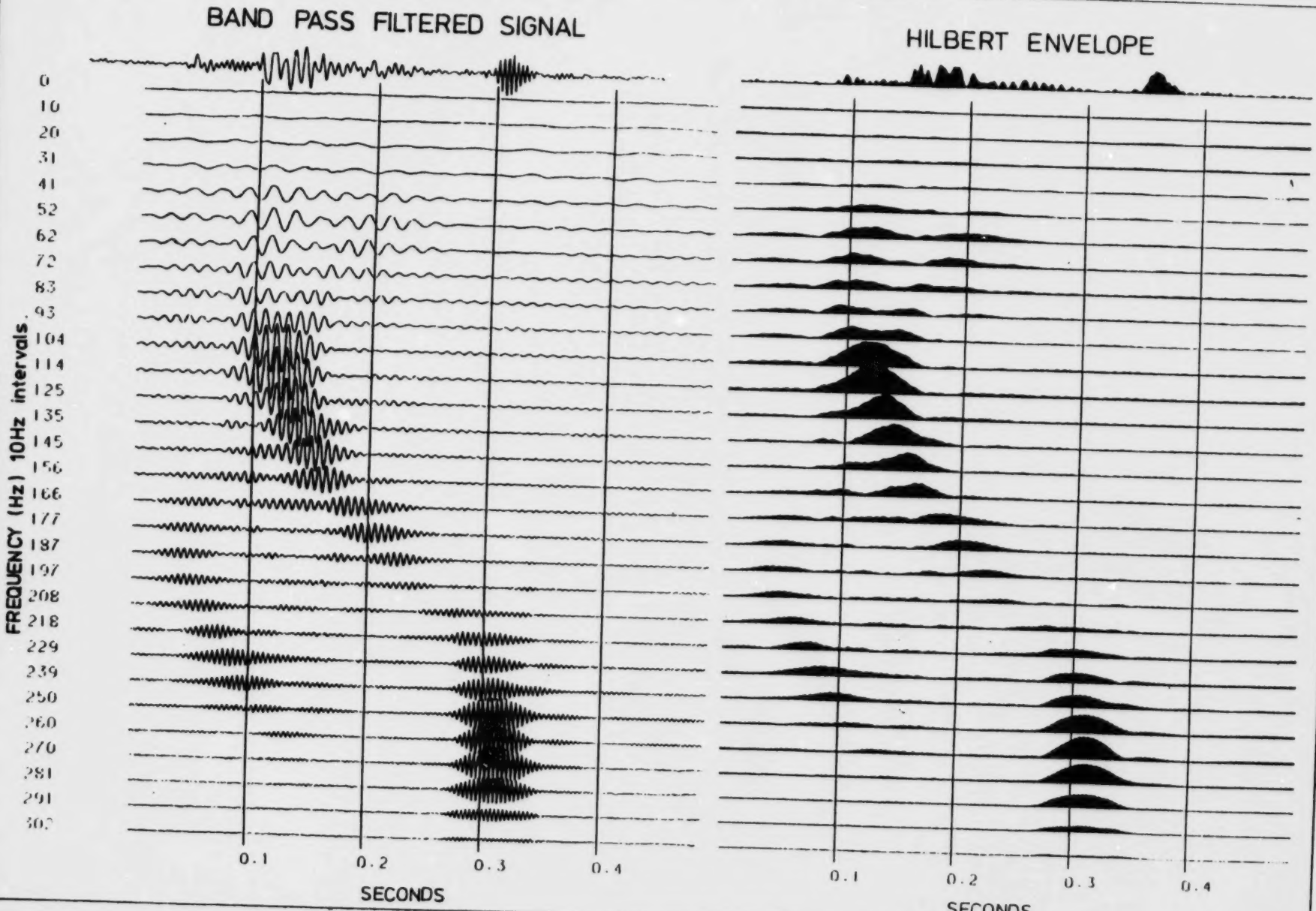
STACKED DISPERSION CURVES FOR THE FIRST LOVE WAVE MODE

FIG. 9



NOTE

Redrawn from Rockburst Prevention with Geophysical Methods, Will M., (1989) Westfälische Berggewerkschaftskasse WBK - Institut Für Geophysik



DISPERSION CURVE AND HILBERT TRANSFORM OF A TYPICAL CHANNEL WAVE

FIG. 10

Golder Associates

APPENDIX A

DETAILED REVIEW OF PREVIOUS DEVELOPMENT AND OPERATION OF MICROSEISMIC NETWORKS IN DIFFERENT COUNTRIES

A1. A Detailed Technical Review

Microseismic monitoring of mines can be carried out from three deployment positions:-

i) Underground Monitoring
ii) Surface systems (including shallow boreholes)
iii) Borehole systems (at seam level)

An overview of previous development and operation of microseismic networks in different countries is presented in the following sections under these three main headings, and summarised in Table A1.

A1.1 Review of Existing Underground Microseismic Monitoring

A1.1.1 Canadian Microseismic Monitoring Systems

Microseismic monitoring systems have been extensively used in Canada in both hard rock mines and in salt and potash mines. No microseismic monitoring systems, however, have been used or tested in the underground coal mining situation. The review of microseismic monitoring systems resulted in this appendix being divided into two broad categories.

a) systems used in hard rock mines and
b) systems used in salt and potash mines

A1.1.1.1 Microseismic Monitoring Systems in Hard Rock Mines

Early Development of Microseismic Monitoring Systems

The use of sub-audible noises as a prediction of rockburst

occurrence was first suggested in 1923 by Hodgson (1958), of the Dominion Observatory, Ottawa, but it was not until 1937 that investigations were conducted by the U.S. Bureau of Mines, in shallow workings, where rockbursts had occurred. The first single channel microseismic system was developed by the U.S.B.M. and tested in both U.S. and Canadian mines. The number of microseismic events in a given time was the main parameter being measured by the equipment. Unfortunately this system was subject to equipment noise problems.

By 1941, suitable apparatus for listening to acoustic emissions in the lead/tin mines in Oklahoma and copper mines in Michigan had been developed. The equipment was also used in Canada at Sudbury and Kirkland Lake (Lakeshore Mine) in October 1941, by Obert (1941) and Obert and Duvall (1942), reported by (Pakalnis, 1984), with up to 100 geophones being used at any one time by the end of 1943.

Further work continued in Canada under the auspices of INCO, at Sudbury, with equipment having a frequency response from 300 to 3000 Hz and an amplification factor of $2x10^6$. Although many events were detected in this bandwidth, no reliable precursors were identified, with the possible exception of an upward shift in frequency of the recorded events prior to rockbursts. A portable listening device was built in 1942 and rock-noise was monitored sequentially for 3 minutes at a time at 160 stations at all levels of the mine, taking three days to cover the entire mine.

Recent Microseismic Monitoring Systems

In Canada, the main interest in AE/MS geotechnical applications stems from the increasing rockburst problems in hard rock mines, particularly in Ontario and Quebec.

According to Udd and Hedley (1985), as of 1985, some 10 multi-channel AE/MS monitoring systems with varying degrees of sophistication, with 8-64 transducers, were either installed or in the process of installation in Canadian Mines. As of 1987, this figure had increased to 14 systems in Ontario alone (Hedley, (in press)). Hanson et. al., (1987) reported that these microseismic systems, are all based on the Electro-Lab 250MP with a maximum of 64 channels. The systems are exclusively operated for real-time source location of seismic events and to provide an indication of magnitude. The principle of these systems is to simply measure the arrival time of a seismic signal at successive geophones of an underground network. As such they are considered to be of limited use for the application envisaged, unless a full waveform capability is available. It will clearly be of no use for in-seam monitoring without substantial modification to the software.

Further acoustic emission research has been undertaken by the NORANDA Research Centre who developed their own microseismic system and also evaluated the McPhar 'Stress Alert', Rock Stress Monitor, finding that it had many serious defects and was totally unsuitable for use in their mines (Momoh et. al., 1989). Their conclusion was that the manufacturer had made modifications to the original design which degraded its performance. They also describe a proposed 32-channel system based on an Electro-Lab 250MP monitoring system with Model 271 transducers and Model 250 Digital processor.

Most of the research studies on microseismic monitoring in Canada were carried out by CANMET, the mining engineering department of Queen's University, the University of Saskatchewan and the ground control/rock mechanics departments of major mining companies. A summary of the research and development work by Queen's University is

given in appendix 2. Recent microseismic monitoring systems used in major underground mines are briefly described in the following sub-sections.

Strathcona Mine, Sudbury, Ontario

The microseismic system used in Falconbridge's Strathcona mine, which consists of five Teledyne-Geotech strong motion accelerometers, was installed both underground and on the surface (Hedley and Udd, 1987). Transmission of the analogue signal from the sensors to the processing unit is by cable. The processing unit is built by Instantel Inc., and is responsible for event recognition and data digitization. Waveform analysis is performed at the Elliot Lake Laboratory of CANMET, and data can be transferred to the laboratory by asynchronous modems. From the available information it would appear that important aspects are addressed in this system, with waveform analyses being performed and the important aspect of event recognition being performed.

Another research programme at Strathcona, described by Davidge (1987), utilises acoustic tomographic imaging of the rock mass, conducted by Queen's University (Young et. al., 1987a), and the collection of full wave microseismic data.

An elaborate system which utilises a PDP 11/73 complete with high capacity disk storage and high resolution graphics terminal were used to receive and store the arrival times of up to 16 transducers. Every two hours source locations are calculated by a least squares algorithm, to reduce the standard deviation of the source location solutions to acceptable limits one or more arrival times are omitted.

The use of a combined microseismic and tomographic survey

is considered to be applicable, with the tomographic survey providing a means to target a microseismic monitoring system.

Campbell Red Lake Mine, Ontario

Microseismic activity associated with pillar bursting has been reported from the Campbell Red Lake Mine, Ontario (Neumann and Makuch, 1989) and the system used at this mine is again based on an Electro-Lab 250MP, which was installed in 1983, with 32 geophones. In 1984, a PDP 11/23 mini-computer was added to the system to enable high speed data manipulation and processing. The system was expanded to 48 channels, with the addition of 16 accelerometers in 1985 and by the end of 1987 the system consisted of 64 channels, all of which were accelerometers, with transducers placed throughout the mine in a series of local arrays (Makuch, 1987).

This system appears to be based on a good philosophy, with the use of local arrays deployed throughout the mine. Assuming that the PDP 11/23 is used for full waveform analysis, it would appear that a very useful system has been developed.

Creighton Mine, Ontario

A 16-channel 250MP microseismic system designed and constructed by Electro-Lab has been used to monitor the microseismic activity in the vicinity of the deepest openings between the 6600 to 7000 feet levels at Creighton Mine, Ontario by INCO Ltd. However, this system was not capable of providing premonitory warning of rockbursts and additional activity at higher levels required an expansion of the system to 48-channels, (Oliver and McDonald, 1989). A fibre optic shaft cable is used to transmit the microseismic signals to the surface (Hedley and Udd,

1987).

It would appear that this system is of little applicability to the Sydney Coalfield, although the use of fibre optic cables is considered to be of use, particularly if the signals are to be transmitted in a multiplexed form which could save direct costs.

Macassa Mine, Ontario

A temporary microseismic network employing 12 geophones was installed at Macassa Mine by Lac Minerals Ltd, in conjunction with CANMET, to determine seismic activity before and after the destressing of a crown pillar. Eight of the 12 channels were connected to a Gould waveform recorder (Hedley and Udd, 1987). The goal is to install a 48 channel microseismic system mainly for source location at the Macassa Division, (Quesnel and Hong, 1987). In a further joint venture with CANMET, through the Canada-Ontario-Industry Rockburst Project, 5 triaxial geophones, also with a Gould waveform analyser, would be installed. This would enable studies of first motion direction.

The ability to conduct studies of first motion direction is an important parameter in the understanding of the phenomenon and should be applied to the Sydney Coalfield. However, the system as it stands is of little applicability, although the basics could be extended, with relevant hardware, to form a useful system incorporating full analysis.

No. 12 Mine, Bathurst, New Brunswick

At the No 12 mine, Bathurst, New Brunswick, an 250MP was installed and started continuous monitoring in October 1986 (Kristof et. al., 1987). The purpose of the system

was to provide source location information, event count rates and magnitudes. However, it was considered that the capture of full waveform data should be for research purposes.

The microseismic system utilised 32 transducers which were type 271 accelerometers with built in amplifiers, a high signal to noise ratio, a sensitivity of 950 volts/g and a flat frequency response in the range 80Hz to 8kHz. Accelerometers were used because of their wide frequency response. The power and signal is carried by cable pairs.

Full waveform recording and analysis should be part of any system deployed, and in the case of the Sydney Coalfield should not be regarded purely as a research tool. It would also be of use to install transducers with a flat frequency response covering a broad range preferably form less than 80Hz.

The objective of the research was to install a full waveform capture system, designed at Queen's University, which would allow for frequency domain analysis and digital filtering. Spectral analysis would also be conducted, with the computation of seismic moments, corner frequency and stress drop. Such analysis was conducted to facilitate the prediction of rock failure in both time and space. Source location is performed by one of two algorithms, either the Least Squares algorithm, or the Four Point Double Tetrahedron SIMPLEX technique (Kristof et. al., 1987).

Such a waveform capture system, including time and frequency domain analysis should be used as part of the system, although ti is envisaged that this should be part of the overall system as opposed to a separate 'add on' unit.

Denison Mine, Elliot Lake

At the Denison Mine near Elliot Lake, Ontario, a reasonably portable high frequency data acquisition system was used, monitoring in the range 50 - 400 kHz. The sensor used in the monitoring trials was a piezo-electric transducer, a type u30D manufactured by Physical Acoustic Corporation. The signals were amplified by a pre-amplifier with a gain of 40dB and transmitted as an analogue signal using 50 ohm coaxial cable. A further power amplifier was used to increase the sensitivity of the system and provide an additional gain of 32dB. The amplified signal was digitized by the micro-computer using a digitizing board with a 12 bit A/D converter and a sampling rate of one million samples per second, to avoid aliasing the high frequency components (Calder et. al., (in press)).

The system appears to be a useful addition to the techniques, but the attenuation at such frequencies would severely limit the detection ability of such a system. A system operating at these frequencies is only applicable in specific circumstances, such as close to the working face or in single entry drivages.

Computer processing of the incoming data was controlled by a priority based multi-tasking programme. Signal processing involved signal conditioning in the time domain, and frequency calculations in the frequency domain. The precursor analysis of the captured microseismic events was based on features extracted from the wave form and the frequency content. Pattern recognition techniques were used to characterise the different waveforms.

Unfortunately, the range of detection of the system was no more than 5m. As the range of detection was so low, areas

in need of such high frequency monitoring need to be determined. This could be provided by numerical modelling and/or event location systems and/or the experience of mining personnel (Semandi et. al., (in press)a). The analysis of the peak waveform magnitude and the centre frequency did not, however, reveal any significant precursory behaviour prior to a rockburst.

The problem of recording incoming data has been addressed in this system, which also allows for the application of feature extraction and pattern recognition techniques, which should be implemented where possible within a system for the coalfield.

Quirke Mines, Ontario

At both the Denison and Quirke Mines, in Ontario, triaxial velocity gauges, with a frequency response of 2-250 Hz have been installed in the floor of underground drifts and stopes (Hedley, (in press)). These are augmented by five geophone sets at the surface, with a frequency response of 8-300 Hz. These were grouted in shallow boreholes, of the order 4m below the surface and on rock outcrops.

At the New Quirke Mine, a system was installed which is described by MacDonald, (1982). It was based around a 16 channel Electro-Lab 250MP system utilising geophones. The system should have the capability of fulfilling the following requirements:-

* to locate the source and calculate the energy of each event
* to determine the relationships between strata noise, pillar damage and mining activities
* to determine the trends in microseismic activity preceding rockbursts
* for the rapid transmission of the available

information

* to assess the stability of pillars and the hanging wall

Signals from the geophones were amplified at source by pre-amplifiers with low impedance outputs. The analogue voltages were connected through screened cable to signal conditioning and filter interfaces at the surface processing unit. The 16 geophones were installed in boreholes to form an array and were connected to a central junction box and power supply by 10000m of 4-way screened cable. The signals are transmitted to the surface via a 200m 25 pair overall screened cable.

The micro-processor 250 MP-1 swept the input signals controlled by a programme in non-volatile memory. When an event is detected the time is recorded from the 250 MP-4 event timer and the arrival time data is stored for use by the 250 MP-2. The 250 MP-2 receives channel numbers and arrival times for each event, and linear equations are solved to calculate source locations and seismic velocities.

Information about the events is stored on a hard disk using the programme MONITOR, running continuously creating files of event data on a daily basis. The output files are analysed by EVENT which rejects spurious events.

An interactive programme INTERR allows the operator to enter geophone coordinates and the assumed seismic velocity to enable the system to calculate source locations and also to look at the data and obtain a status report. The programme DIGIPLOT is used when mine plans are digitized for the presentation of event locations, it is also used to edit and update existing files. To display the source locations on the VDU, PLOT is used which combines the results of EVENT and DIGIPLOT, from this trends can be identified.

Whilst systems based around this system dominate microseismic monitoring in hard rock mines it may not be of use in the Sydney Coalfield without major modifications to the software.

East Malartic Mine, Northwestern Quebec

Bourbonnais (1984) describes a microseismic system operating in the East Malartic Mine, in Northwestern Quebec to monitor activity associated with rockbursts. The sensors used were 10Hz geophones with a flat frequency response up to 2.5kHz mounted in boreholes. The signals were pre-amplified prior to being transmitted by cable. At the monitoring facility the system consisted of a filter interface; a threshold detector; a RBM digital micro-processor, programmed to determine arrival time information; an energy integrator; and a printer. Source location determination was accomplished using three techniques; the Generated Block Method, the p-wave Direct Solution and the p-wave Least Squares Method. Some rockbursts occurred with a precursory pattern of an increase in activity followed by a quiescent period immediately prior to the rockburst, and some occurring with no precursory warning. Whilst this is in part applicable to the development of a system, it would require modifications to both hardware and software to be applicable to the Sydney Coalfield.

A1.1.1.2 Other Applications of Microseismic Monitoring

Systems for Salt and Potash Mines

Another major use of microseismic monitoring in Canada has been in Potash Mines in Saskatchewan, where seismic events of magnitudes up to 3.6 on the Richter scale have been recorded (Gendzwill, 1984).

A permanent underground monitoring system has been installed at the Cory Mine of PCS Mining to elucidate the relationship between mining activity and the failure of the carbonate rocks overlying the potash (Vance and Mottahead, 1989). This study focused on the research and operation both of low frequency and high frequency microseismic systems. This system uses a 16 geophone array and again utilises an Electro-Lab 250MP which is linked to an IBM-PC. More recently an Electro-Lab 500MP has been used at the Cory Mines. However, it lacks the essential facility of full waveform recording.

Such a dual frequency system is a useful approach to the problem, however, the system is again limited by the use of the Electro-lab and the lack of essential full waveform recording, and the applicability is therefore considered to be limited.

The continuing research included the implementation of the 'Integrated Acoustic Network', the so called IAN System™, which consisted of low frequency and high frequency measurements. The system incorporates the microseismic source location hardware already used, an RM-6 multichannel rock monitor, developed by Integrated Sciences Inc., following the principles of the Microseismic Roof Fall Warning System. The Rock Monitor, a high frequency seismic recorder which operates in the frequency range 20-60 kHz has also been used in PCS mines. It is claimed that they are capable of predicting roof falls, according to tests carried out by the U.S.B.M. in U.S. coal mines.

The system comprised 16 transducers, of which 15 were geophones, which were installed in boreholes 5m deep, and maintained the initial spacing of 200m. Pre-amplifiers were used and these were mounted near the collar of the boreholes. The sixteenth transducer was a triaxial set of

accelerometers, linked to an integrator to obtain an estimate of the energy of the events.

As the monitored area was some 5km from the mine shaft and it had been considered that it would have been prohibitively expensive and technically difficult to transmit the signals to the surface, an underground monitoring station was established. Most of the processing was completed by the hardware located at this station.

The initial processing is performed by an Electro-Lab 250MP, which scans the incoming data and senses the onset of an event. An event is 'recognised' when any geophone exceeds a preset threshold level, once this has occurred event timing begins. It is considered that seismic signals are below 50Hz so the system incorporates a 100Hz low pass filter to reduce noise not removed by electrical grounding. An IBM PC is linked to the 250MP allowing data entry, such as transducer location co-ordinates. It also scans the 250MP's buffer to determine whether an event has occurred and been recorded, if an event has been recorded the data is down-loaded to the IBM.

These are then processed by source location programmes, a SIMPLEX algorithm and a cube stepping algorithm called CUBE, originally developed by Gendzwill (Gendzwill and Prugger, 1989). The programme CUBE is iterative and steps through trial locations distributed about the face, edges and centre of the cube, it compares the errors and moves the cube until the centre location has the minimum error. Having achieved this the dimensions of the cube are halved and the process repeated. This shrinking process is repeated until the cube is acceptably small. The programme has the additional feature of applying time delays for refracted ray paths according to Snell's law.

The IBM computer has peripheral devices which consist of a Centronics printer, Amdex monochrome monitor, two Teac floppy disk drives and a Develcon modem. The modem is used to link the underground computer system to the surface system. The computer routinely interrogates the modem to establish whether a 'request' has been issued from the surface to transmit data. If a 'request' has been issued the computer automatically transmits the stored data to the surface and enquiries whether or not it should delete the stored data.

On the surface data is received by a Commodore Superpet with a Commodore 8250 disk drive, and Epson printer, Tektonix plotter and a Develon modem. Software has been developed to generate various displays of activity, which include plots of locations on digitized mine plans, colour coded to energy level and graphs of activity in terms of number of events, or energy level, against time. A good correlation was seen to exist between the microseismic activity and load (Mottahead and Vance, 1987).

Clearly the advantage to record full waveform data would be advantageous, but this system does use source location software that should be considered for use within the system developed for the Sydney Coalfield. Other than recommending the software it would appear that the system is of little applicability to the problem.

A serious brine inflow occurred at the Rocanville Division of PCS Mining, the dissolution effects and structural changes produced considerable microseismic activity (Vance and Mottahead, 1989). A temporary microseismic system was deployed at Rocanville which consisted of two Terra Technology DCS recorders with three geophones each; these were previously used at the Cory Division. The digitized seismograms were recorded on tape and subsequently replayed through a Terra Technology Reader, with data

being transferred to an Apple II with two floppy disk drives and a printer. Initially, the system was installed with three geophones on the surface and three underground. A decision was eventually made to deploy both recording units underground. The recorded data was analysed on the Apple II, the first arrivals on each channel being picked for use in the SIMPLEX iterative source location algorithm.

It has been suggested, by the authors, that this equipment whilst being the best available at the time, but by today's standards it is slow and difficult to use and therefore is of limited applicability to the problem. It does, however, use what is considered to be an effective source location algorithm.

The Microseis monitoring system, designed at the University of Saskatchewan, was installed in potash mine of Saskatchewan in 1985. The system runs on a Intel SYS310 computer with Multibus architecture and dual processors, a slave for A/D digitizing and trigger tests and a master for interpretation and plotting. Microseis features 16 channels, expandable to 32, sampled up to 500 samples per second per channel, with 12 fixed bits for a dynamic range of 72 dB. This has been replaced by the Microseis II, based on the Intel SYS320, a 32 channel system capable of sampling at a cumulative sampling rate of 30000 samples per second, with data stored on a 220Mbyte hard disk. Event recognition has first interrupt priority on the master processor so no data is lost while the computer is performing another task. Data is stored on a hard disk, typically 140 megabyte capacity, and data can be transferred to floppy disk or streaming tape. Seismograms can be retrieved from the disk and plotted on the screen or on a plotter. Event summaries can be listed on a printer or plotted on a map.

Microseis includes advanced interpretation. A phase picker runs automatically on events and a preliminary location is determined. The automatic picker works well only on clear, noise free signals. For most events, the waves are displayed on the screen and the operator picks the phase with a cursor. Up to 16 channels can be displayed at once with arbitrary scales. Data can be filtered prior to picking. Event location is accomplished using a version of the SIMPLEX algorithm, developed at the University of Saskatchewan (Gendzwill and Prugger, (in press)).

With the Microseis, events have been accurately located far outside the geophone array as well as inside the array. If the SIMPLEX is used in a uniform earth model, it can solve for three coordinates of the events and for the seismic velocity of the earth. The SIMPLEX is also used with ray tracing techniques to solve for event location in a multilayered earth but the velocity must be specified beforehand. Source and receivers can be located anywhere in a multilayered earth dipping at any angle and with no restrictions about velocities of any layer. Critically and non-critically refracted paths are searched for the fastest raypath. Take-off directions in spherical coordinates at the source are calculated for each ray in the layered earth and first motion polarities can be plotted on an equal area stereo net for the interpretation of fault plane solutions. Maximum amplitude of each seismic waveform is measured, converted to ground motion using individual gains, and a best fit magnitude estimate is made. Clipped signals are excluded from the magnitude estimate. A Microseis system with computer and software costs of the order of $50,000. Geophones, telemetry and amplifiers are not included in this price.

This computer based system represents one of the few commercially available analysis units that could be of

interest to the establishment of a system within the coalfield. It is, however, limited by the number of channels it is capable of handling.

The Microseis system has been installed at two mines, K1 and K2 belonging to the International Minerals and Chemical Corporation (Canada) Ltd., near Esterhazy, Saskatchewan.

At K2, channels 1-8 were connected to underground transducers, one being a triaxial set, whilst channels 10-12 were connected to surface transducers. The geophones used were Mark products model L-1 which were used in pairs underground, fixed to the roof and buried approximately 30 cm. in soil on the surface. Data is telemetered, along cables using frequency modulation with Teledyne-Geotech and Sprengrether equipment. Source location is accomplished using ray tracing and the SIMPLEX method using a layered earth model (Gendzwill and Prugger, 1987).

The system has also been used, to good effect, to monitor hydro-fracturing of a test well at a heavy oil recovery site operated by Amoco Canada Petroleum Ltd., at Gregoire Lake, near Fort McMurray, Alberta.

In 1989, a Seismic Monitoring System developed by Weir-Jones Engineering was installed in a Saskatchewan mine. The Weir-Jones system runs on a PC-AT computer with a minimum of 1 megabyte of RAM and a 16 megabytes hard disk and a 16 megahertz clock speed. It uses a DAS 16F A/D digitizing board. An optical disk, maths co-processor a mouse device, printer and plotter are optional. The system includes 16 channels with a maximum of 500 samples per second with a sixteen bit fixed gain conversion for 96 dB of dynamic range. Triggering is accomplished by the STA/LTA algorithm and a minimum number of channels must be triggered within a specified time window. Waveforms can

be plotted and event summaries printed in various forms.

The Weir-Jones system includes advanced interpretation. A special feature is the ability to add new interpretation routines easily to the software in Turbo Pascal 5.0. An automatic phase picker is included but the manual picker with cursor is generally used. Data can be filtered before picking if desired. Event location is accomplished using the Leighton and Blake algorithm to determine an initial solution and then the SIMPLEX for the final X, Y, and Z coordinates, using a fixed velocity. A horizontal layered earth model can be used for geophones in the mine or for geophones on the surface. A magnitude is estimated by picking maximum amplitudes of waveforms and fitting the data to the magnitude equation. The cost for the computer and software for this system is about $50,000. Geophones, telemetry and amplifiers are again extra.

Whilst the system has many features considered necessary for the acquisition and interpretation hardware and software, it is considered that the number of channels required to monitor the mining areas of the Sydney Coalfield would be much higher than offered by this system and consequently seems to be of limited applicability.

A1.1.2 Microseismic Monitoring Systems in the United States

The occurrence of gas outbursts are relatively limited in U.S. Coal Mines, partly due to the fact that most active mines are relatively shallow and do not suffer from high stress conditions. However, it is anticipated that as mines become deeper and as more complex deposits are mined, the incidence of outbursts will increase. Relatively few microseismic studies have been conducted in U.S. coal mines, although it has been noted that in recent years there has been an apparent increase in gas outbursts

in a number of U.S. salt mines (Hardy, 1987a).

The first documented rockburst, is believed to have occurred in 1904, in the Atlantic Mine, in the Copper district of Michigan. A severe rockburst finally caused closure of the mine in 1906. At the present time, the only area where bursting is a problem is the Coeur d' Alene metal mining district of northern Idaho.

The earliest research on rock bursting conducted by the U.S.B.M. began in the late 1930's. The micro-seismic technique was first mentioned as a way of studying rockbursts in the Coeur d' Alene district, soon after the first fatalities occurred in 1941 (Bolstad, (in press)). It was not until the mid 1960's, however, after methods for locating the source of seismic activity became available, that microseismic techniques were applied.

Several types of microseismic systems have been developed to monitor rockbursts. The mine wide systems have generally used between 20 to 30 single axis geophones to triangulate the source and triaxial sensors to determine magnitudes.

The Denver Research Centre has used the approach for almost 20 years at the Galena Mine and is now expanding and re-designing its single stope microseismic systems into a mine wide network. The present system routinely monitors one or two stopes, utilising 16 geophones per stope, and has been updated to improve the data quality and minimize data loss. A new modular system has been designed, which uses a 32 channel remote data collection unit for each stope. Of the 32 channels, 16 are set to a low gain and the remaining 16 to a high gain to extend the dynamic range of the system. Each stope module is fed to an underground instrument room where each remote unit has an associated processing computer. Data is then

transmitted to the surface through a fibre optic cable. A vertical, single channel, short period seismograph is located on the surface and the digitized data can be incorporated into the analysis.

This system seems to be based on a good philosophy, it is however, possibly unlikely that such a system would be certified for use within the coalfield. Whilst it has been designed around a different mining method, the modular nature of the system could be applied by deploying the modules around individual panels. It would be preferable to move the individual processing computers to surface locations for such applications. Some signal conditioning would probably be required underground, prior to signal transmission.

Brady (1987) describes microseismic research at the Galena Mine, Wallace, Idaho. Microseismic research which has been conducted since 1973 has centred around three types of system:-

* surface seismograph networks of triaxial sensors in a quiet area.
* a mine-wide microseismic system, with a large spacing between geophones.
* a local microseismic system, to monitor a small section of the mine, with geophone spacings of the order of tens of metres.

It is suggested by the U.S.B.M. that all three are required to adequately characterise a rockburst, or even a gas outburst and assess the relative stability of the mine. Each system should be present in a complete monitoring network. This view is also supported by the authors of this report. It is, however that this particular system would be applicable to the Sydney Coalfield.

The surface systems uses triaxial geophones, 210/220 broadband transducers with a period of 10-30Hz, and associated electronics for the analogue recording of short period seismic events. The buffered pre-amplified analogue signal is spilt, with one going to a Teledyne-Geotech single axis helicorder and the other being digitized, recorded and finally sent by landline to the Denver Research Centre.

Blake and Leighton (1970) of the U.S.B.M. obtained much higher frequency information from hard-rock mines in Idaho (Galena Mine, Wallace, Idaho) using accelerometers cemented in underground boreholes with cable transmission to a central recording facility (7-track analogue tape recorder) and they carried out early work on the location of rock noises (Leighton and Blake, 1970).

Leighton and Steblay (1975) describe the work which was being carried out by the U.S.B.M. in deep coal mines in Western Colorado where what they describe as coal 'bounces' were a major hazard. These would appear to represent bumps or coal bumps. Geophones with a bandwidth from 15 to 250 Hz were used to detect the events which were discriminated and analyzed on the RBM (Blake, 1977). Measurements in the ultra-sonic range were made using the 36-44 Khz band to detect the high frequency signals associated with roof falls, although this was only effective over short distances of about 21 m because of the rapid attenuation suffered at these high frequencies.

The limited details of this system appears to confirm the usefulness of a low frequency bandwidth for monitoring events generated by coal mining activity. Similarly the use of the ultrasonic range for measurements is seen to be useful, however, only over short distances as noted. This 'two pronged' approach to monitoring is considered to be applicable to the coalfield, although it is unlikely that

the precise specifications would be used.

Acoustic emission monitoring was becoming a widely used tool for mine stability studies and Langstaff (1977) describes a 24-channel minicomputer based acoustic emission system employed at the Star Mine, part of the Coeur d' Alene mining district in Shoshone County, Idaho. At that time it was the deepest Lead-Zinc mine in North America, with associated serious burst problems. The results were rather problematical, with occasional seismic precursors to bursts, bursts without precursors and precursors without subsequent bursts. Later work reported by Blake (1984a), from the Star Mine, was similarly equivocal with only 30% of bursts having clear precursors and some very large bursts (Richter magnitude 2.6) appearing to have no obvious associated precursors.

From the available information the decision as to whether or not this system is applicable is problematical. However, it is unlikely that it is applicable, partly as a consequence of the limited number of channels, it could, however, form part of the overall system.

In contrast to these rather disappointing results, Gibbons (1980) has reported small, mid-range frequency, events at about 30 Hz from White Pine Copper Mine, Michigan and quotes:

> 'These signals are small in amplitude but consistent in form and frequency content. The mid-frequency events appear prior to less than half of the total falls observed. However, whenever they appeared, a fall followed soon afterwards. In times of quiet, or immediately after a fall, these mid-range signals are virtually non-existent. Their source mechanism probably is either the coalescing of micro-fractures into larger "micro-fractures" or layer separations

independent of the micro-fracturing.....'

This study showed that very low frequency signals in the 25-35 Hertz band can be seen just prior to falls of rock in mines. The link between their occurrence and falls seems rational. This type of event, with this frequency content, will later be discussed at some length in the context of the surface monitoring of outbursts at Cynheidre Colliery, U.K.

There appears to be limited information available on this system, however, it is suggested that the system monitors what appears to be an important part of the spectrum.

Leighton (1984a) described a system developed with the Bureau of Mines to monitor activity prior to, and associated with, outbursts. He considered that the ultrasonic equipment developed during roof failure warning research was ideally suited to monitor activity in the frequency range 40kHz to 110kHz. The frequency response enables the system to be used in close proximity to the working face, as it is insensitive to man made noise.

The system uses sensors which are composed of a lithium sulphate crystal, with a flat frequency response from 10-110 Khz. The output of the sensor is connected to a pre-amplifier, both of which are mounted to the roof.

The lower part of the spectrum is filtered out, which results in a system response of 36kHz to approximately 110kHz. Signals are transmitted via cables to a data acquisition unit (DAU) where the signal is processed and conditioned for transmission to the recording facility. The DAU performs two signal processing functions; the first is an envelope detector which produces one count for each event and the second is energy processing; the signal is rectified and passed through a threshold detector. The

Bureau found that the time above the threshold was a good first order approximation of the energy. The energy and event count rate data are transmitted, after a pre-set time interval, to the recorder by a cable link or a 'through the ground' low frequency telemetry link to a 'data recorder' consisting of two printers. It was observed that the energy-event ratio was a superior technique for analyzing ultrasonic data and is reported to improve the results when analyzing outburst data.

Leighton (1984b) again describes the use of high frequencies, in the range 40kHz to 110kHz in acoustic emission monitoring to perform near source monitoring for outbursts at the Coal Basin site, with some reasonable results using energy/event ratios rather than straight event counts.

Precursors were demonstrated to be present some 15 minutes before impending outbursts with the obvious limitation that the extremely high frequencies used imply severe attenuation over distances as short as 25 metres. Leighton (1985) reported the preliminary results from the testing of an automated real-time coal mine bump monitor being developed by the U.S.B.M., Denver. A commercial implementation of this monitor was developed as the McPhar Rock Monitor and an assessment of this was carried out by Ersavci (1989), who conducted tests on a long-wall panel in the Kitt #1 Mine, Phillipi, West Virginia which produces metallurgical grade coal (production at 1 Mtonne per year). Immediate problems with electrical interference were noted, which were improved by shielding and it was found that transducer coupling was extremely important at these high frequencies. It was considered that there was some potential for the use of this type of equipment for the detection of roof falls, but that much further work was required to obtain consistent results.

The ultrasonic systems described by Leighton and associated software appears to have some applicability to the prediction of outbursts. Although it would appear to be useful an assessment of the commercial application suggested otherwise. The main drawback with the system, would appear to be a function of limited monitoring range at such high frequencies which entail frequent re-deployment of the equipment or its use only in specific locations.

Hardy (1987a) reported that many mines in Coeur d' Alene district have installed arrays of transducers consisting of 20 or more geophones underground. These are connected to pre-amplifiers, the outputs of which are connected by cables to a centrally located junction box. These are connected via a 72 conductor pair cable to the surface monitoring facility. At the central monitoring facility the signals are first filtered with a band pass filter, having a pass band of 20 to 2500 Hz, these signals are then fed to a pre-processor, an RBM unit. The outputs from the pre-processor are monitored by a suitable computer, an IBM system/7 at the Star and Lucky Friday Mines, this provides source location, energy, and time of day information. Source location is performed by a least squares algorithm.

The system described by Hardy (1987a), would again appear to be applicable in part to the problem in the coalfield. It is likely, however, that more than 20 transducers would be required to adequately monitor the situation. With additional signal conditioning with the mine environment it should be possible to transmit data to the surface over possibly cheaper cable.

Testing of a prototype high frequency microseismic monitoring system has been conducted in a number of coal mines and provided an early warning for 20 out of 23

ground failures, with pre-cursor times in the range of 5 to 92 minutes (Hardy et. al., 1987a). The system was developed as a Roof Fall Warning System under a U.S.B.M Contract, and the commercial development of the system has been undertaken as a one channel high frequency AE/MS monitoring system and has been manufactured by Integrated Sciences. The system is battery operated, self contained, portable and intrinsically safe. This type of system has met with considerable success in coal mines and also Canadian Potash mines.

Whilst this single channel system has reportedly met with considerable success in both coal and potash mines in Canada, it was developed as a roof fall warning system and it is unclear if it would have the ability to predict outbursts. If the system was applicable it has the disadvantage of being only a single channel system which would require frequent redeployed and would not be able to monitor all working areas.

Several microseismic monitoring programmes have also been conducted over the last 20 years in the coal mines of the Eastern Wasatch Plateau, Utah, (Wong (1984); Wong et. al., (in press)).

In 1984, a three dimensional, high resolution network of analogue and digital seismographs was operated in the vicinity of two coal mines beneath Gentry Mountain, (Wong, (1985); Wong et. al., (in press)).

There is little information about the systems reported, however, the use of a high resolution, three dimensional network is considered to be essential to the development of an appropriate system for the coalfield.

At the Hecla Mining Company's Lucky Friday mine, a deep lead-silver-zinc mine located at Mullan, Idaho, an

underground microseismic system was installed. It consisted of 34 single axis geophones and 5 uniaxial accelerometers deployed throughout the mine's working levels. The array was connected to a real time data acquisition system, designed to capture and record all seismic events within the frequency range of 60 - 2500 Hz, that fulfilled the pre-requisite of being detected on at least 5 sensors. The signals were then processed by an on-line micro-computer which used the U.S.B.M's seven channel least squares location programme to calculate the source location of the events (McWilliams et. al., (in press)). Williams et. al., (in press) describe the underground system in which the mining areas are monitored by a mine wide network of geophones and accelerometers, which were linked to two 16 channel transmitters which telemetered the data to a surface receiving station. This is in turn connected to an HP85 computer and data was stored on magnetic tape and as paper charts.

This system whilst appearing to be useful in terms of the Sydney Coalfield is restricted by its frequency range and detection pre-requisites. Assuming that it could be modified in terms of bandwidth, the use of triaxial sets where possible, increasing the number of channels, and modifying the software it would appear to be applicable to the coalfield.

Applications of acoustic emission techniques in other types of geological structures were also taking place at this time and in particular we note micro-acoustic studies of a LNG reservoir in rock salt (Meister, 1980; Durr and Meister, 1984), gas storage in sandstone in Coalville, Central Utah (Lingle and Francis, 1980) and monitoring of the New Haven gas storage facility using transducers deployed in boreholes ranging in depth from 1-300m, as reported by Hardy (1980, 1984a, 1984b, 1987b); Hardy and Mowrey (1984). An array of commercially available

geophones were deployed at the surface, in boreholes and underground, for cavern stability studies. Notch filters were used to minimise 60 Hz electrical noise and active band pass filters (1-50Hz) were also used to reduce both the 60 Hz noise and higher frequency.

The philosophy of installing transducers to form a three dimensional array, deploying transducers in many different locations is advantageous and should be utilised in the development of a system for the Sydney Coalfield.

A1.1.3 Microseismic Monitoring Systems in the United Kingdom

In the United Kingdom, outbursts have represented a serious problem in the anthracite zone of the South Wales Coalfield, where anthracite of very high quality is mined. Cynheidre Colliery, Dyfed, has been the site of 114 serious outbursts since it opened in 1960 and, as a result of this, an Outburst Research Centre was instituted in 1961, in an attempt to determine useful precursory phenomena which might provide warnings of imminent outbursts.

Tapes recorded using an underground accelerometer and a portable tape recorder did show conclusively that there was in-seam microseismic activity and that this increased at about the time of roof collapse, as the powered supports were advanced. Spectral analysis of these events suggested they had a frequency spectrum ranging from 400Hz to 1250Hz (Hughes, 1973).

Subsequently, a spontaneous outburst, which occurred during March 1981, was successfully recorded and, notwithstanding the lack of accurate timing information and contamination of the signal by crosstalk from the colliery telephone system, it did conclusively show the

presence of frequent 'pouncing' prior to the outburst.

Thus early phase of monitoring provided evidence of the ability to record microseismic activity associated with outbursts. However, the equipment used for this study is out of date and would not be recommended for use in this problem.

As part of the programme to monitor Cynheidre an underground microseismic monitoring system was developed by the University College of Cardiff (Brown and McDonald, 1984; Rigby and Wardle, 1984; Rigby and Bolt, 1989). The system comprised a four-channel set of geophones grouted into boreholes in the coal seam with FM telemetry to the surface for on-line detection and processing. The system appears to work reliably and well, picking up three main types of seismic event with dispersive characteristics showing them to be propagating within the seam.

They show excellent correlations with methane emission from the face, however, no outbursts occurred during the period of full-time deployment and it is not clear whether this type of seismic activity, while clearly correlated with mining extractive processes, has any bearing on the mechanism or prediction of outbursts.

This system shows that such systems are useful in monitoring microseismic activity and could form the basis of a system for use in the Sydney Coalfield. An expanded system using state-of-the-art signal conditioning and a full suite of interpretation and analysis software could be utilised in the coalfield to great effect.

A1.1.4 Microseismic Monitoring Systems in West Germany.

In a mine on the Ruhr, F.R.G., a 12-channel underground system has been used to record 100,000 events in a four month period (Will, 1980). A portable, intrinsically safe, instrument developed jointly by WBK (Bochum) and Lennartz for monitoring the seismic seam-reaction was used during destressing drilling in outburst prone areas (Will, 1984a, 1984b). Frequency analysis of the events shows that the signals received were mainly in the frequency range 700-800 Hz, whilst drilling noise is in the range 200-400 Hz, so band pass filtering can be utilised to remove the drilling 'noise'.

It would appear that this system has been used effectively in West Germany to monitor the effects of destressing drilling. While it is not in itself applicable, the basic components of such a system are applicable to the Sydney Coalfield.

A system designed for use during Longwall Retreat Operations has been comprehensively described by Will (1984c) and Will et. al., (1985). The system designed for this monitoring consists of 16 channels, each of which has a maximum bandwidth of 1000Hz and an A/D conversion precision of 12 bits, which represents a dynamic range of 72dB, with one extra bit per word of additional information. Data is recorded digitally and, depending upon the number of channels selected, the recording bandwidth can be increased to 16kHz per channel. The on-line statistics of time of event, triggered geophone, maximum amplitude and energy content are calculated by the computer on surface.

A total of 32 geophones, Geospace HS-J were used which have a natural frequency of 28Hz, with a relatively flat response to 2kHz, however, there is a slight drop in

sensitivity from low to high frequencies. The signals from the geophones are pre-amplified and transmitted to a central underground monitoring station, along with a 10kHz control signal. At the underground monitoring unit, 16 of the 32 geophones are selected for further transmission, this selection is accomplished by commands issued from the surface. The selected 16 channels are multiplexed at the central underground unit and passed through a pre-amplifier and anti-alias filter before being passed to an A/D converter. The resulting PCM coded signal is transmitted to the surface using a single pair cable. Depending upon the length of the cable used for transmitting the signal to the surface, amplification and signal shaping may also be required. All the underground components are decoupled from the surface devices using opto coupling, to maintain intrinsic safety.

At the surface the PCM signal would then again be pulse shaped and then demultiplexed to produce 16 parallel signals. The signals are passed through a 16 channel digital trigger device. Microseismic events are recognised to have occurred if their amplitudes exceed the average noise.

Once an event has been recognised it is processed, by a NOVA 3D, 16 bit computer, with 256 kbytes of core capacity and several mass storage and peripheral devices. These include a double hard disc drive, a floppy disc drive, two high speed tape drives, alphanumeric and graphic displays, and a printer/plotter.

The signals are recorded on tape using the DMA-mode (Direct Memory Access) of the NOVA 3D, the signals can be delayed in a delay line register with a maximum delay of 500ms. The delayed, demultiplexed and D/A converted signals were recorded using a 16 channel fibre optic chart recorder, which is started by the trigger.

WBK and Lennartz have now developed a fully digital PCM underground system which can multiplex 24 channels deployed as 6 x 4 geophone packages and then telemeter these to the surface for on-line analysis on a MicroVAX II. Details of this system are only available in German at present, but a translation of this promising development is being sought (Will, 1989).

The system described by Will et. al., (1985) appears to work well achieving the objectives for which it was designed. The system has been updated substituting more modern equipment, described by Will (1989). It is suggested that such a system would be of use in the Sydney Coalfield, the only disadvantage being that the system would have to be re-deployed occasionally as mining proceeds, the system is also designed for retreat mining operations, and a slightly different approach would be required if advance mining techniques were exclusively used.

A number of other studies have been conducted using transducers installed underground in the coal seams of a number of mines, most of which have been initiated to study the effects of mining and the efficiency of destressing techniques on seam stability, these are described by Baule and Rao (1979) and Will (1980, 1984a, 1984b).

Work of a similar nature has been carried out in Europe for some time in coal and potash mines Buchheim, (1958). Of particular note is the work of Reinhard (1955, 1956) who carried out monitoring in the Cevennes coalfield, where some 6000 outbursts occurred.

Systems designed and deployed for monitoring the efficiency of destressing techniques show the basics of systems, it is unlikely, however, that such systems will

be applicable.

Microseismic systems have been used in the Asse 2 salt mines in West Germany as described by Hente et al., (1989). They use a low frequency system and a high frequency system together. The low frequency system has a band pass of 1 Hz to 90 Hz and records continuously on paper charts and also on digital tape at 178.5 samples per second with a 12 bit A/D for 72 dB of dynamic range. The high frequency system monitors 8 channels in a triggered mode using a bandpass filter of 4.5 Hz to 300 Hz. Event recognition uses an amplitude threshold. At least two channels must trigger within a specified time window. Events are sampled at 1482 samples per second per channel are recorded on digital tape with a 12 bit A/D fixed gain. Three seconds of buffer delay are included to allow time for starting the tape. They are replayed using special playback equipment. Data is transferred to a computer and the source location is computed using the Ingalada method as published by Cete, (1977). Ingalada's method is similar in some respects to the Leighton and Duvall method.

A system operating within the lower part of the frequency range is considered to be of use for studying coal mining induced seismicity. The system does feature full waveform recording which is considered to be an advantage. It is, however, considered that this system is not applicable to the Sydney Coalfield.

Durr and Meister, (1984) describe the use of acoustic emission equipment for pillar evaluation in a German salt mine. Their single channel piezoelectric sensor was operated from 100Hz to 100kHz. Total system gain was 86 dB. An amplitude threshold trigger of 70 microvolts was used and in routine use events were counted and the totals printed. For special studies an oscilloscope and tape

recorder were used to capture waveforms.

This system whilst useful for the purpose it was designed is unlikely to be applicable to the Sydney Coalfield.

A1.1.5 Microseismic Monitoring Systems in France

Dechellette et. al., (1984) and Revolar et. al., (1986) have described the operation of a 4 - channel underground system in the Provence coalfield, France, directed by CERCHAR, Ecole des Mines in Nancy and have established relationships between face advance and energy released per shift. They have attempted to identify the onset of outburst-prone conditions using departures from this relationship, and their results appear to show high negative residuals prior to an assumed outburst, which they ascribe to the storage of elastic energy prior to their release in the outburst.

The aim of the work was to develop a monitoring system which would complement the 'drilled test hole' technique. The monitoring system which was developed comprised four geophones deployed from 200m to 400m ahead of the coal face and a surface data acquisition and analysis system. These investigations indicated that suitable criteria existed for the classification of zones approaching a dangerous situation and the general overall surveillance of a specific mining operation could be established.

During the last ten years, two different techniques have been applied to the monitoring of seismic activity associated with mining by CERCHAR, Centre d'Etudes et Recherches de Charbonnages de France. Revalor et. al., (in press) have described the phenomena of rockbursts in French coal mines as the catastrophic failure of the coal seam, which they in turn describe as a 'coal bump'. In such cases the roof remains intact but the floor is noted

to heave and there is a low emission of gas accompanying the events.

A first approach is the 'seismo-acoustic monitoring' method which has been applied to one longwall face, where, based on the energy release rate, dangerous areas are detected during the mining operations. The monitoring system uses between 4 and 7 vertical component geophones, capable of measuring a particle velocity in the range 0.3 to 20 mm/sec with a frequency range of 10 to 300Hz. These are located in either the roof or the floor and are moved periodically as the face advances. The signals are transmitted via telephone cables. A band pass filter is applied to the data with a frequency range of 10 to 300 Hz.

The data is processed by a on-line computer which digitizes the incoming data at 1500 samples/sec. Triggering is performed by the simple function of exceeding a pre-set level on 2 or more channels. The events are recorded both on a photo-sensitive recorder and digitally as event characteristics.

The second technique is that of 'seismic monitoring' in which a larger network is used to locate seismic events and to study their focal mechanisms. This network utilises between 8 and 12 geophones both vertical component and tri-axial and having a frequency range of less than 30 Hz. These are located both at the surface and underground. With this system, the transmission method is more sophisticated, using FM modulation and transmitting the signal either by radio telemetry or cabling. The signals are band pass filtered in the range 1 to 20 Hz. Triggering is again performed by the signals exceeding a pre-set level on 3 or more channels. Digitization is performed automatically with a sampling rate of 50 to 100 Hz. Whole waveform data is recorded on a continuous

chart recorder and also stored on magnetic tape or hard disk.

It is suggested that this approach to the problem is the ideal design philosophy with which to approach monitoring the Sydney Coalfield, and this 'two pronged' approach is discussed at length in Section 4, although the system as specified may not be able to adequately characterise the anticipated mining induced seismicity. It is suggested that a large mine wide network should be installed which would assist in the location of outburst prone areas and target the deployment of a second smaller panel based system.

A1.1.6 Microseismic Monitoring Systems in Sweden

Microseismic monitoring work in Sweden is rather limited. AE/MS monitoring was undertaken at the Boliden mine in Sweden during the 1950's and 60's in the Laisvall mine (Krauland and Westerberg, 1977) using 9 narrow-band geophones at frequencies of the order of 1000Hz (± 200Hz), built by ADELTA AB Sweden. The system recorded increases in AE/MS activities for about 1 day prior to roof falls.

From this limited information it is suggested that the frequency response of these systems would not be able to monitor events generated during mining in coal measure sequences and is therefore, not considered suitable to this situation.

Båth (1980) suggests that rockbursts were apparently relatively rare phenomena in Sweden, however, as mining occurred at greater depths and at higher speeds several iron ore mines experienced relatively large rockbursts, such as Malmberget, Dannemora and Grängesberg. As a consequence a local geophone array around the Grängesberg mine to monitor rockbursts. This enabled the

discrimination of different types of events by comparing the records with those from permanent seismograph stations.

The establishment of local arrays is a useful technique in monitoring seismic activity and should be considered further in the design of a system for the coalfield. The equipment used was, however, not specified so whether this is an applicable system cannot be ascertained. It is, however, unlikely that it would fulfill the requirements envisaged.

A1.1.7 Microseismic Monitoring Systems in Australia

Major developments have taken place in Australia, with microseismic monitoring systems being deployed in both hard-rock and deep coal mines. Godson, Bridges and McKavanagh (1980) reported the initial operation of a 32-channel automated system for the on-line detection and location of rock-noise, which was used to monitor the Mount Isa Lead-Zinc and Copper mine, although a great many problems were experienced in the commissioning of this system.

The use of a multichannel system for automated on-line detection and location of events as used, is suggested to be the preferred methodology for the development of a system for the Sydney Coalfield.

McKavanagh and Enever (1980) developed an underground single channel system for monitoring AE/MS in coal mines. Signals in the 100 to 5 kHz range were recorded prior to outbursts in West Cliff Colliery, N. S. W. and a reduction in the rate of microseismic activity was noted in the 10 minute period immediately prior to the outbursts. Warning times of 0-17 minutes was claimed to be attainable. Further development was aimed at producing an

intrinsically safe audio/visual warning system for mounting on a continuous miner. Grezl, Leung and Ahmed (1980) contended that earlier work conducted by CSIRO at West Cliff Colliery has been inconclusive. Grezl et. al., (1984) built on this work and deployed underground systems to predict outbursts at the Broken Hill Proprietary Company Ltd., (BHP) at both Leichardt and Metropolitan collieries with accelerometers in the coal rib and a system bandwidth of 2 Hz to 1.5 Khz.

They clearly detected in-seam Channel waves which gave characteristic coal dispersion curves. Enhanced background seismicity occurred for 17 days before a 25 tonne outburst, again with a reported reduction in activity several shifts before the outburst.

It is suggested these systems, whilst being only single channel, have been successful, although it is known that certain problems have existed during outburst prediction. Notwithstanding this, the methodology of installing transducers at seam level is applicable to the coalfield.

A1.1.8 Microseismic Monitoring Systems in Japan

Outbursts have been a major problem in Japan, with an explosion occurring at the Ohyubari Mine, Hokkaido in 1981, with 93 lives lost. A two channel underground system was installed in Akabira and Ohyubari mines and seismo-acoustic activity was monitored during advance boring for methane drainage (Nakajima et. al., 1984).

Acoustic Emission studies have been conducted at Sunagawa mine since 1976, Horonai mine since 1978 and Akabira mine since 1979, using Dunegan/Endevco and Marubun equipment. The signals are amplified underground and transmitted to the surface (Watanabe et. al., 1984). The two channel system consisted of two transducers, pre-amplifiers,

acoustic emission instrumentation, a tape recorder, and a real time spectrum analyzer when necessary. The transducers, accelerometers were Endevco 5200M5 with a high sensitivity of 250m v/g and a flat frequency response from 2 to 5000Hz. Watanabe et. al., (1984) concluded that with the system deployed acoustic emission activity was monitored proceeding during and after rock or coal and gas outbursts. The system allowed for accurate monitoring of the local fracturing activity and was useful to investigate the mechanisms of outburst occurrence. This system has been successful in monitoring activity pre-, during and post outbursts, but was limited to two channels and as such is unlikely to be applicable to the Sydney Coalfield.

A system with such a small number of channels is not really applicable to the Sydney Coalfield. However, it was not designed to monitor the mining environment but has a rather specialised function.

Isobe (1974) and Isobe et. al (1976, 1977, 1979, 1980, 1984) reported a combined surface and underground system employed at the Sunagawa Coal Mine near Bibai, where three rockbursts occurred in 1968, which were detected by a seismic observatory more than 100 km away, with Richter magnitudes of 1.9 to 2.8. They have carried out comprehensive studies of the energy releases associated with hydraulic coal mining of steeply inclined coal seams. They also claimed an accuracy in their hypocentral locations of 7-10 metres.

From the reported results of this work it would appear that the system performs well and it is suggested that it supports the need to deploy a three dimensional array within the coalfield to monitor both Lingan and Phalen. This system was clearly developed to monitor the mine environment and locate events and is considered that such

a system should be part of the overall system.

A gas outburst occurred in a cross cut just after blasting in the Sunagawa Coal Mine. The gas outburst produced 60,000m^3 of methane and 1,600m^3 of coal dust which blocked the cross cut and extended for 100m from the face. The microseismic activity associated with the outburst was monitored by a mine wide seismic array which consisted of eight geophones, installed underground and on the surface (Sato and Fujii, 1987). Anomalous microseismic activity associated with the outburst lasted form two minutes. The sources of the activity was located by means of a joint hypocentre determination.

In essence this work would seem to be similar to that reported by Isobe in terms of spatial coverage. It would appear to have performed well identifying periods of anomalous activity associated with an outburst. It again vindicates the methodology of deploying a three dimensional array to monitor Lingan and Phalen.

Sato et. al., (1989) describes a system which has detected more than 20,000 events with local magnitude greater than -2.5, occurring during the extraction of two long-wall seams at the Horonai Mine, Hokkaido.

It appears form this description that a sensitive panel based, or 'district' based system has been developed and it is considered that this should form part of the overall monitoring system.

Mining at the Horonai Mine is conducted at depths between 985 and 1125m and monitoring has been conducted since 1980, using an underground array of accelerometers or geophones, or by using a near surface array of geophones (Sato and Fujii, 1988). The mine wide seismic array developed consisted of 10 stations, of which 6 to 8

stations are placed on the surface and the remainder placed in underground roadways near the mining panels.

Velocity type geophones were used, with built-in Tokyo Sokashin QS-11B pre-amplifiers which are intrinsically safe (in Japan), and have a frequency and damping constants of 1.5Hz and 0.7 respectively. Detected underground seismic signals were digitized at the recording station, whilst signals detected by surface stations were immediately digitized at the site with the digital signals being transmitted to a recording station. Any seismic signal, exceeding a preset level, was recorded automatically by a triggering method on standard magnetic tape. The seismic events are located using an interactive least squares method. Gutenberg Frequency-magnitude relationships were established giving b-values of 1.01.

The use of mine wide systems combined with the use of a surface array, providing three dimensional coverage has again been used in this system and reinforces the concept of producing a three dimensional array. The use of digital storage and the recording of the events should be addressed in the system to be developed for the Sydney Coalfield. However, unless an 'intelligent' triggering system is developed triggering should be avoided, or important information may be lost.

At the Miike Coal Mine, which is an undersea coal mine, pure coalbursts have occurred with no associated gas, while working below 550m with an immediate sandstone roof. The conditions prevailing appear reminiscent of those pertaining to the No.26 Colliery, Nova Scotia.

A 12 channel source location system which was installed to monitor the microseismicity consisted of 12 seismometers situated in roadways surrounding the district being monitored, with amplifiers, filters, A/D converters and a

mini-computer (Kaneko et. al., (in press)).

The concepts of surrounding an area with an array affording good coverage as in this case is rational and this sort of array could be considered to form part of the overall system to be deployed within Lingan and Phalen.

A1.1.9 Microseismic Monitoring Systems in China

The Peoples Republic of China has more than 1,000,000 men working at risk from outbursts, in some 1000 mines. Roof failures in hard rock mines are also a major problem; Li (1989) reported the case of the Pangushan Tungsyen Mine in Jiangxi province where 373 stopes collapsed successively over the course of a few days.

Microseismic monitoring, however, is still in its relative infancy in China. Li (1989) of the Safety Technology Research Institute, Ministry of Metallurgical Industry, in Wuhan, described the design of two portable, single-channel AE monitoring facilities, which have been used in both hard-rock and coal mines to predict stope falls and coal bursts. The first unit has a frequency range of 20Hz-20kHz and a sensitivity of 90mV/g. and the second, a hand-held unit, has a bandwidth of 800-1600 Hz. The recorded results showed some increase in AE rates prior to some of the rock failures, but other failures occurred without any apparent warning. However, an anomalous increase in emitted energy was reported some two days prior to a coal burst at the Mentougu Mine.

The use of single channel units either hand-held or permanently mounted would not seem to fulfill the requirements of a system to be deployed in the coalfield. The system has, however, met with limited success with anomalous levels of activity being reported preceding a coal burst.

Apparently, similar systems are presently employed in a number of mines in China. A more comprehensive joint study of the relationship between acoustic emission and gas emission during drilling was carried out co-operatively between the Fushun Coal Research Institute and Hokkaido University at Yangquan First Coal Mine using accelerometers deployed in boreholes with monitoring being conducted on a Dunegan/Endevco 300 AE monitor (Zhang et. al., 1987).

These systems would again appear to be specialized systems for use in studies of acoustic emission relating to gas emissions during drilling. Unless such a facility is required it is considered unlikely that such a system would be applicable to the system designed.

Laboratory studies are being conducted at the Central Coal Mining Research Institute in Beijing where high frequency (> 100 kHz) equipment is being used to investigate failure properties of coal and associated sedimentary rocks. It is hoped that this would lead to the development of a practical system for underground applications.

A1.1.10 Microseismic Monitoring Systems in India

Major rockbursts have occurred in the Kolar Gold Mines, South India, since the beginning of the century and both surface and underground seismic networks have been used to monitor them. Microseismic research has been conducted by the staff of the Bhabha Atomic Research Centre at the Bharat Gold Mines Limited mine. Two seismic networks have been developed and these are described by Subbaramu et. al., (1989). One of them is a surface system which covers an area of 3km by 6km and uses 7 Geospace sensors having a band width of 5Hz to 180Hz. The surface network is used to delineate zones of high seismicity. The other monitoring system is an underground network which has been

established in the deeper levels, covering an area of 100m x 100m. Similarly this network uses 7 Geospace sensor, but this network has a bandwidth of up to 5kHz with data recorded on a 24 channel analogue tape recorder.

The system developed to monitor in this hard rock mine is again based on two components, a surface array and an underground array to produce a three dimensional system. This system also benefits from using sensors with a broad frequency response. The concepts of this system should again be considered in the design of a microseismic monitoring system.

The microseismic research groups of both the Department of Mining Engineering and Department of Applied Geophysics of the Indian School of Mines in Bhanbad have developed similarly disposed systems. At one particular site, a tri-axial geophone has been installed on the surface and a series of underground geophones have also been installed.

The use of tri-axial geophones is considered to be useful for use in the system to be deployed within the Sydney Coalfield, although it is appreciated that a much larger system would need to be developed. The additional information gained should outweigh the problems associated with a larger system.

A1.1.11 Microseismic Monitoring Systems in the U.S.S.R.

As some 3000 outbursts had been experienced in the Donetz Basin the application of microseismic monitoring techniques was deemed to be of use. In the early 1950's the Makeev Safety in Mines Research Institute of the U.S.S.R. used 'listening apparatus' similar to that designed by Obert (1941), in an attempt to forecast sudden outbursts of coal and gas in mines. These subjective

techniques met with limited success, but were later taken up and developed by the Geophysical Institute of the Academy of Sciences of the Soviet Union, under whose auspices acoustic recording apparatus was developed. This work was carried out by the Skochinskii Mining Institute (Moscow) and the Donetz Council of the National Economy, (Antsyferov, 1966). More than 150 faces were monitored at 37 collieries with some promising results.

A1.1.12 Microseismic Monitoring Systems in Eastern Europe

During the 1960's microseismic monitoring work has being carried out in coal mines in Czechoslovakia (Simane, 1963). Stas et. al., (1971) reported that microseismic research associated with coal mining has been active for some years. More recently Dlouhy (1976) and Roček et. al., (1975) discussed the development of automated microseismic monitoring facilities and their application to various rockburst problems in bituminous coal mines. A number of studies have been described by Broz (1975) and Simane (1975) in hard rock mines, but little information has been published in recent years. It is suggested, however, that mine wide systems are in use at some coal mines.

An on going microseismic investigation in Czechoslovakia was described by Holub (1985) and Holub et. al., (1987), from the Doubrava Colliery in the eastern section of the Ostrava-Karvina Coal Basin, where an intrinsically safe, (for Czechoslovakia), digital, 3-channel system has been developed and deployed underground, where both surface and underground data are being monitored and analysed. A six station network has been developed at the Klando Coal Mines, with two stations underground and the remaining 4 at the surface (Rudajev et. al., 1985).

Although these systems have a limited number of channels they again have built up systems to provide three dimensional coverage and whilst the system itself may not be applicable the concepts are.

Coal mining related microseismic research in Poland through the late 1970's has been extensive (Hardy, 1987a). With both in-mine and surface mounted transducers being employed in mine studies. The data is regularly used for the scheduling of various types of destressing programmes and for warning of possible major rockbursts and outbursts.

Extensive work is currently taking place in Poland (Gibowiz, 1984), where it is believed that there are a total of 30 underground microseismic networks (Gibowicz, (in press)). However, at the present time, there is little information available as to the equipment specifications. Both stationary multi-channel apparatus and portable single-sensor apparatus have been developed (Trombik and Zuberek, 1977), with later development of a semi-automated system using Bruel and Kjaer type 4340 accelerometers, B&K 2616 pre-amplifiers and a Telefunken MAS 24-4 tape recorder. They noted increases in microseismic activity for several hours preceding major rock-bursts.

The Polish systems developed would appear to have met with some success and again in the most part advocate the establishment of both surface mounted and underground arrays, deploying high quality equipment. Again the methodology of deploying transducers at as many levels as possible is indicated and should be used where possible in the Sydney Coalfield.

Trombik and Zuberek (1980) also reported a series of source location studies, which have been conducted in a Polish longwall coal mine, again to evaluate the effects

and efficiency of destressing blasting. These studies have been carried out using geophones, which were installed both ahead of the longwall faces and in worked areas which are supported by hydraulic back fill. The data was recorded on a multi-channel tape recorder in the frequency range of 20-1200Hz.

This system like many others has been designed to address a particular problem, that of monitoring the efficiency of destressing blasting and as such would not be used for the problem encountered unless specifically required.

According to Sombati (1983), at the Hungarian Central Institute for Mining Development, simple acoustic tomography and preliminary microseismic studies have been undertaken in a number of Hungarian coal mines.

During the 1980's, the Hungarian Central Research Institute for Physics has developed a wide range of microseismic monitoring equipment (Peter and Pellionisz, 1980 and Peter et. al., 1981). This includes a mobile 32 channel monitoring capability and associated computer facilities for data processing and storage. The system is capable of monitoring and processing signals in the frequency range 50kHz to 2MHz.

The systems reported from Hungary are considered not to represent a solution to the problem under investigation, partly as a function of the frequency range utilised.

A1.2 Surface Microseismic Monitoring

Whilst the majority of microseismic monitoring programmes have used transducers underground, within the working areas, a surface microseismic network has many advantages. A surface system remains easily accessible at all times, requires no certification, can monitor the whole extent of

the workings, without necessitating the re-deployment of the network as mining progresses, and is remote from mining noise.

A1.2.1 Canadian Surface Microseismic Monitoring Systems

Under the Canada-Ontario-Industry Rockburst Project, seismograph units were to be installed at Red Lake, Elliot Lake, Sudbury and Kirkland Lake to obtain permanent records of the larger seismic events and their magnitude (Hedley and Udd, 1987). Microseismic systems were also to be installed around Campbell, Quirke, Strathcona, Creighton and Macassa mines. These systems were to consist of triaxial strong-motion geophones, including processing units for event detection and data digitization. The capture of complete waveforms would allow for the study of first motions, peak particle velocity, seismic energy and spectral frequency, to investigate the causes and mechanisms of rockbursts.

The acquisition of complete waveforms is important as a considerable amount of information is then available to elucidate the modes of failure. Whilst such a system would be difficult to implement, the concepts of acquisition should be used in the system deployed.

A macro-seismic system was developed and deployed under a contract by Noranda, as a research tool at Elliot Lake in March 1987. Labuc and Momoh (1987) comprehensively describe the system installed near the CANMET laboratory.

It was composed of 5 triaxial sensors in an approximately $1km^2$ array, designed to monitor a section of the mine. The transducers were installed in boreholes from the surface. It was suggested that a mine wide underground network could be achieved by the addition of expansion modules. An Electro-Lab 250MP system equipped with broadband

accelerometers deployed underground, is generally used to monitor events with magnitudes, M, less than zero.

The surface system was designed so that it would have a dynamic range of at least 60dB, and would attenuate signals over 300Hz. Testing of the system revealed that an overall signal to noise ratio of 75-80dB had been achieved over the frequency band width of 0.5-300Hz.

Originally the sensors used were the Terra Dynamics ADR-711, which were active and had self contained circuitry. An electronic feedback loop was contained within a modified geophone, producing a servo-accelerometer type transducer which has several advantages over a standard geophone. Unfortunately, during the first lightning storm, 10 of the 15 transducers simultaneously failed, so it was decided to revert to standard geophones.

Signals were transmitted from the sensor array to the receiver by fibre optic links (Labuc et. al., 1987). This mode of transmission was selected as it would be immune from electromagnetic interference. Noranda carried out a cost comparison between suitable electrical cable and the fibre optic equivalent, which showed that fibre optic cables were economically competitive. However, it must be borne in mind that the suitable fibre optic cable was designed and manufactured by CANSTAR Communications a subsidiary of Noranda. A single fibre optic cable is used to transmit the data from one triaxial set of sensors. This is achieved by using three, multiplexed, high frequency carrier signals, modulated by the output of the associated geophones. Off the shelf optical transmitter and receiver modules, having bandwidths of 10Hz-10MHz, are used to transmit and receive information through the optical link. Temperature stability is maintained by temperature compensation of the modulation circuits and automatic frequency tracking at the receiver.

Data analysis was performed by a Masscomp DN5400 (although this has now been superseded) comprising a 1MHz multichannel data acquisition module, high speed processor, high resolution graphics, and a 71Mbyte hard disk with tape backup.

A data acquisition programme runs at a high priority, ensuring 24 hour operation. It sets the clock, A/D converter and sets up 7 buffers for data transfer. It also opens a channel to the PIPE, a service routine which is called to check if an event has occurred. An event is detected when a 4 point moving average exceeds a preset trigger level on any of 16 channels. Once an event has been detected the preceding 0.2 seconds and following 0.6 seconds of data are stored to file, its name being internally generated. The file name is also written to the PIPE, which notifies the demultiplexer routine that there is data to process. If an event has been detected on more than one station, the data is also converted to acceleration and written to an ASCII file, channel by channel.

The graphical display programmes are operated either manually or automatically at a low priority. The operation is mouse controlled and has the option to enhance p and s wave plots by the rotation of the axes. The data from all 5 sites can be displayed simultaneously, or, alternatively, any one of three axes from each site. The arrival times for the p and s waves for each channel can be picked, again using the mouse, and these can be saved in a parameter file. There are two other programmes available, which allow the velocity or displacement time series to be viewed. Also, the data can be transformed into the frequency domain and the corner frequency and plateau can be determined, both important parameters in the understanding of microseismic event mechanisms.

The data manipulation software is a non-interactive application calculating seismic parameters and source locations, consisting of many sub-routines. The parameter file is read by one subroutine, passing data to other subroutines. Source location is performed by both the SIMPLEX algorithm, and also the CANSPLOC routine, a direct inversion method. A separate routine allows the demultiplexed data file to be read. The peak particle velocity is calculated by another subroutine and yet another subroutine computes other source parameters, such as seismic energy, first motion direction and seismic movement. Finally, there is a subroutine to write the calculated parameters to an updated parameter file. There is also a separate programme which automatically restarts acquisition should the computer crash.

Labuc and Momoh (1987) concluded:-

> 'Practical low cost seismic monitoring networks using fibre optic transmission are feasible and can be implemented using readily available components. The use of multiplexed frequency modulation on an optical channel allows for easy implementation of triaxial sensor installations that are immune to transmission line noise pickup without the expense of digitization at the source.'

This system, although a purely surface based system embodies many of the attributes that are considered to be essential for a system to be developed for the Sydney Coalfield and many of the features have been included in the design in Section 4. From tri-axial sensors, through transmission system processing software and hardware this represents one of the most applicable systems, to monitor the mine environment. Some of the components of this system,have now been superseded and it would have to be significantly modified for the underground environment.

This system would not appear to be commercially available as it has been 'constructed' from off the shelf components, and it should therefore be straight forward to construct a similar system.

Within the Sudbury area a local, three station, digital seismic network has been set up with two of three seismograph stations deployed on the South and West rim of the Sudbury Basin. The network monitors the mines of INCO Ltd and Falconbridge Ltd (Plouffe et. al.,(in press)). The system uses short period Teledyne - Geotech S13 vertical component seismometers, including a 60Hz package, in surface vaults.

At the outstations, the data is digitized producing 16 bit data samples from a 12 bit A/D converter with a minimum detectable ground motion of 2nm/sec. The dynamic range of the system is 126 dB with a frequency range of 1 - 16Hz.

The outstations are linked to a central recording station, at the Science North processing centre, by dedicated telephone lines, where the data is recorded on drum recorders (Hedley and Udd, 1987). The incoming signals are also connected to a PDP 11/73 computer, which monitors continuous data from the outstations, and saves any triggered events using a STA/LTA trigger algorithm. The computer system has a disk capacity of 110 Mbytes.

The data is transferred to Ottawa where data processing and analysis is performed on a MicroVAX II. This consists of a KA 630 CPU with 9 Mbytes of memory, a DHV-11 8 port DMA terminal multiplexer, a RD53 71 Mbyte system disk with an RQDX3 controller and two Fujitsu M2333 280 Mbytes user disks, an EMULEX QD32 controller and a DEQNA Ethernet controller (Plouffe et. al., (in press)).

The seismic analysis monitor package (SIM) is used to display, filter and scale the data. The PIK program generates data for input into the location program (LOC), which calculates hypocentre and magnitude parameters. It is possible to calculate other source parameters using additional routines.

CANMET is planning to install two further networks to surround Falconbridge's Strathcona Mine and INCO's Creighton Mine.

It would be difficult to install such an array within the Sydney Coalfield although it is considered that a component of the overall system should be deployed on the 'surface'. The concepts of this system are rational and the use of such arrays with digital storage should be considered.

Rio Algom's Quirke Mine, near Elliott Lake, Ontario, is monitored by a microseismic surface network. The system has been developed by NORANDA under a CANMET contract and was deployed on the surface.

The sensors were located in shallow boreholes and originally consisted of 5 triaxial IDR 711 accelerometers. These were, however, subsequently replaced by Geospace GS-40B, 8Hz geophones with a sensitivity of 0.2 V/cm/sec (Semadeni et. al., (in press)b).

The signals are frequency modulated, multiplexed and transmitted by fibre optic links to a central location, where the optical signal is converted back to an electrical signal. This is then demultiplexed, filtered and digitized by a minicomputer, at a sampling rate of 1000 samples/sec. A 0.8 sec window, which includes a 0.2 sec pre-trigger, is sampled (although this has been identified as being inadequate) and is being increased to

a window length of 1.5 seconds to ensure that complete waveforms are recorded. Events are considered to be valid and saved where signals exceed a pre-set trigger threshold on 3 of the 5 sites. Signal analyses are preformed, both in the time and frequency domains. Event locations are determined by an Electro-Lab 250MP source location system operated by the Quirke Mine.

The vertical axes of the five surface sensors are connected to the 250MP to augment the underground array. Parameters such as first motion, p and s-wave arrival times, peak particle velocity, seismic energy and attenuation are determined. Some of the seismic source parameters determined are corner frequency, frequency plateau, seismic moment, source radius and stress drops.

The problems associated with the lack of full wave acquisition of the 250MP have been addressed in this system, enabling the computation of important parameters to the study of failure. It would appear that good quality transducers have been deployed, importantly as tri-axial packages, and uses what should prove to be a good transmission system. Whilst this system uses many features that should be considered, the system itself is unlikely to be used as it stands.

In Saskatchewan local surface seismic networks are operated to monitor potash mines. A surface system was operated from 1980 to 1984 by the University of Saskatchewan under a research grant from the Potash Corporation of Saskatchewan. The array consisted of six elements in a 800m by 1600m pattern, which were established on the surface approximately 1km above the mining horizon of the Cory Mine (prugger and Gendzwill, 1983). Each element contained two vertical component Mark L-1 4.5Hz geophones in series, with signals telemetered by twisted pair wire. Signals four seconds in length were

recorded digitally on cassette using Terra-Technology DCS-302 three channel event recorders with 5 millisecond sampling and featuring triggering and pre-event memory. The events were subsequently played back on an Apple II-plus microcomputer. Source location being performed by a SIMPLEX algorithm. At the time the equipment was installed it was the best available, however, by today's standards it is slow and difficult to use, and consequently would not realistically be recommended.

A1.2.2 Surface Micro-seismic Monitoring Systems in the United States of America

The surface monitoring of microseismic activity associated with longwall coal mining has been accomplished with the use of an array of 15 geophones, mounted in shallow boreholes augered to bedrock where possible (Mowrey and Hardy, 1978). The array used 14Hz Geospace Type GSC-11D geophones mounted in the PC-25 marsh case, with a flat response from 10-500Hz. These were connected to low noise pre-amplifiers with a 40dB gain, located on the surface, which were in turn connected to post amplifiers with a 50dB gain, in the monitoring facility. A set of filters is used to attenuate all frequencies above 1000Hz and below 10Hz. The outputs from the filters were connected to a seven channel FM recorder and a visicorder, (UV chart recorder). Source locations have been calculated with the use of the travel time difference method.

The advantages of surface mounted systems is well documented although there is clearly a problem in establishing such a system in the Sydney Coalfield. This system would appear to be somewhat dated now with the majority of the components now superseded. As such we would not recommend the use of such a system.

Hardy (1980, 1982) also reported on the use surface systems used during 1970 - 77, in longwall coal mine studies. The system used consisted of 15 transducer at selected sites, with geophones cemented into holes augured to bedrock. At any one time, seven transducers were used. During monitoring of the New Haven gas storage facility in Michigan, two systems were incorporated. One was an eight channel system optimized for detailed multi-channel recording on magnetic tape and the other was a 3 channel system with a helicorder for long term recording. For remote sites, a three channel radio telemetry system was developed for use at the site. In all cases, acoustic emission signals were detected and analyzed.

Again it is difficult to envisage the use of such a system to the solution of the problem within the Sydney Coalfield.

Wong (1984) and Wong et. al., (1989) described the use of a 16-24 channel, high gain, short-period (1Hz) microseismic network in the Paradox basin to monitor seismicity associated with coal mining beneath the Book Cliffs, where events as large as 4.5 magnitude have occurred together with subsidence from a Potash Mine. He detected activity ascribed to collapses within the coal mine which triggered earthquakes on pre-existing thrusts beneath the Colorado Plateau and also low-level seismicity associated with the subsidence due to a potash solution mine.

This mine was subsequently monitored in detail by a 9-station digital, high gain, short period network. Two types of event were recorded; tectonic events like earthquakes and unusual, harmonic, surface-wave-like events.

The system used within the Paradox Basin seems to have been effective, producing good results, including the recording of what are described as unusual harmonic, surface-wave like events, which have been noted in several other studies. It would be difficult to install such an array in such an environment

A1.2.3 Surface Micro-seismic Monitoring Systems in the United Kingdom

Westbrook et. al., (1980), Kuznir et. al., (1980, 1982, 1984), and Kuznir and Farmer (1983), carried out a considerable period of monitoring of mining-induced seismicity associated with coal extraction in the North Staffordshire Coal Field, U.K. They recorded events as large as magnitude 3.5, using standard global seismological Willmore Seismometers at the surface and identified events associated with the collapse of the waste, with implosive mechanisms, and also pillar collapse, which was the origin of the largest events which had shear mechanisms.

Whilst this has clearly been a successful system, and shows the uses of a surface array. However, only an element of the system should be considered to be a 'surface' component.

The only surface system deployed to monitor seismicity associated with outbursts sensu-stricto was commissioned at Cynheidre Colliery, Dyfed, S. Wales. Using a network of five vertical component surface Willmore seismometers deployed in a 6 km by 6 km cross array, it was possible to detect, identify and locate microseismic activity associated with normal mining activity, (extraction of coal), and the subsequent collapse of the waste, and to make preliminary correlations with the rate of advance and hence the volume of coal extracted.

This 'normal' activity consists of impulsive seismic events which show the usual sequence of arrival of seismic phases expected form the brittle failure of a rock mass, ie p (compressional) and s (transverse) waves propagating with normal velocities (V_p = 3500 m/s and V_s = 2000 m/s) and can easily be located using normal seismological hypocentral location algorithms. More importantly, a completely new type of seismic activity was recognised which appeared to be associated with the microfracturing of the coal and the emission of methane during periods of abnormal face conditions. Such 'outburst' activity appears to be associated with emergent, monochromatic events with a dominant frequency of 32 Hz with very slow and variable apparent velocities of propagation across the colliery.

This type of 'outburst' activity is rarely seen when face conditions are normal but can rise to levels in excess of 100 events/hour immediately prior to an outburst. A real-time, on-line micro-processor based monitoring system was developed to monitor the levels of activity on each individual channel and to issue audible alarms to the Colliery Control Room operator. This was used successfully, in conjunction with the stress dissipation technique of pulsed infusion firing (Davies et. al., 1987), to control a serious gas emission incident on 19 February 1986 when more than 8,500 metres^3 of methane were released in a controlled manner (Styles et. al., 1987a, 1987b, 1988).

In the case of Cynheidre, microseismic events were easily recorded from workings at a distance of more than 6km. It is, however, appreciated that a subsurface network would have assisted in the location of microseismic events. Further, it must be appreciated that although the microseismic monitoring network established over the Cynheidre workings was purely a surface system, the techniques discussed can equally be applied to a

judiciously established underground system. It would be preferable, however, to establish a combined surface and subsurface network where possible.

At Cynheidre, the microseismic network was deployed in order to monitor and discriminate microseismic activity associated with mining and particularly to investigate whether there are precursors to outbursts, and, if so, whether these could be used as a predictive tool, or an aid to management, for the safe working of the colliery. As a consequence of the many outbursts that had occurred within Cynheidre, mining proceeded in a very restricted manner, governed by a Code of Practice. The microseismic network was therefore linked to a micro-processor that monitored the incoming data in real time and issued warnings to the Colliery management at times of potential outburst risk.

The microseismic system was used as a management tool and is believed to be the first such system to control an outburst-prone colliery. The integrated monitoring system allowed the mine to obtain exemptions for some of the regulations and to mine more productively, thus making the operation profitable. It was considered that the monitoring method, combined with a specialised destressing technique, pulsed-infusion firing, resulted in the mine being worked for more than four years without an outburst occurring.

This system is commercially available and clearly proved the ability to monitor a mine effectively with good results from the surface. It was used as a management tool to control an outburst prone colliery. Whilst the usefulness of the system is evident only the methodology of the system of using a surface array to form part of the overall three dimensional array should be considered for use in the development of a system for Lingan and Phalen.

A1.2.4 Surface Microseismic Monitoring in West Germany

The problems of outbursts in West German coal mines has been the subject of extensive research using microseismic techniques. Baule (1977), Casten and Cete (1980) and Will (1984b) have described a number of investigations in which arrays of permanently installed surface transducers have been deployed to detect and locate sources of activity in a number of coal mines in Ruhr district.

Recently the development of a four channel system for use in coal mines has been presented by Hahnekamp (1984). and the development and use of a mobile telemetry system for use in remote areas, was described by Steinwacks (1988).

These West German systems again sow the applicability of using a surface system as a component of an overall system, although again such systems would be difficult to deploy in the environment pertaining at the site.

A1.3 Borehole Systems

Acoustic emission measurements made in deep boreholes have been used in two main areas. The first is in observing seismo-acoustic activity before, during, and after hydraulic fracturing of hydrocarbon reservoirs (both gas and oil) (eg. Dobecki 1989) and the second is in monitoring in geothermal reservoirs, of which the principal sites have been at Fenton Hill, New Mexico, (Pearson and Albright, 1984), Rosemanowes Quarry, U.K., (Baria et. al., 1989) and in the Kakkonda field, Japan, (Niitsuma et. al., 1985). All of these applications use downhole tri-axial seismometer or accelerometer packages. It is possible to obtain accurate locations from a single tri- axial sonde, because the azimuth can be determined from hodograms (particle motion phase diagrams) and the range can be determined from the time between the arrival

of the p and s phases, which is a reliable estimator of the propagation distance to the event. In addition, by using digital equipment, with accurate registration between the orthogonal components, the degree of shear-wave anisotropy (s-wave splitting) can be determined. It has been shown that this anisotropy can be used to determine the presence of aligned dilatant microfractures and hence the principal stress directions (Crampin, 1987).

Recently, Styles and Emsley, reported by Jackson (1989) have carried out an experiment where eight-component packages, two vertical geophones, and six horizontal component geophones spaced at 45 degree intervals, were grouted into three boreholes in a coal seam at a depth of more than 1000 metres. Calibration of the system was possible using shots fired from a coal seam between 100 and 500 metres away, allowing the p and s-wave dispersion curves to be determined. Seismic waves within coal seams travel as guided horizontal Love waves and hence have a velocity which is strongly dependent on frequency. Spontaneous seismo-acoustic events caused by the collapse of the waste were detected on these sondes permitting locations to be calculated using the hodogram method. This is much simpler than in the geothermal case, because of the guided nature of the waves, the arrivals of energy are constrained to propagate within the coal seam and the problem is therefore only two-dimensional. It appears that measurements made using the low-frequency compressional p-wave at 30 Hz can give locations accurate to better than 20 metres and this would be improved if corrections were made for velocity anisotropy. The results of this work are preliminary and were reported by Jackson (1989). These early results do, however, appear extremely promising, as the quality of the data are extremely good because a deep borehole is a quiet seismic environment.

Additionally, studies of the amount and direction of the shear wave velocity anisotropy, of events propagating through an area, may reveal the presence of dilatant micro-fracturing developing within the coal or sandstone prior to the onset of outburst-prone conditions. Further analysis of these data is being carried out at present at Liverpool University, England.

Borehole systems are effectively those deployed in deep boreholes as opposed to holes drilled to locate transducers as close as possible to bedrock, such systems have been included in this discussion to be both complete and also discuss the merit of such systems. Such work is effective and promising but unlikely to be of benefit unless deep boreholes are either available or likely to be drilled either for exploration purposes or purely to install instrumentation for the purpose of microseismic monitoring.

TABLE A1/1

Golder Associates

				SYSTEM					PROCESSING				
CANADA													
Region	Mine	Resource	Application	Transducers	Transmission System	Conditioning	Recording/processing hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
Ontario, Sudbury	Strathcona	Nickel	Rockbursts	Teledyne-Geotech Strong Motion Accelerometers Underground/Surface	Analogue By Cable		Instantel Inc event recognition data digitization			Waveform analysis Elliot Lake Laboratory		Hedley and Udd, (1987)	Of little relevance although waveform analysis is performed
Ontario, Sudbury	Strathcona	Nickel	Rockbursts				PDP 11/73 16 channel capability		Least squares		Enables rockburst prone areas to be determined	Davidge, (1987)	This is combined with tomography which is an applicable additional method
Ontario	Campbell Red Lake		Pillar Bursting Rockbursts	Accelerometers Local Arrays Underground			Electro-lab 256MP PDP 11/2364 channel capability				Revealed critically stressed areas, although did not give precautionary warning of rockbursts	Neumann and Makuch, (1989)	Based on a good methodology of local arrays
Ontario	Creighton	Nickel/Copper	Rockbursts	Geophones Underground	Fibre Optic Shaft Cable		Electro-lab 256MP 48 channel capability				Not capable of precautionary warning	Oliver and McDonald, (1989). Hedley and Udd (1989)	Of little relevance except the transmission system
Ontario	Macassa	Gold	Destressing Crown Pillars. Rockbursts	5 Triaxial Geophones			Gould waveform recorder 12 channel Gould waveform analyser 48 channel			First motion studies	Capable of detecting and locating events	Hedley and Udd (1987) Swanel and Hung (1988)	The ability to conduct first motion studies should be applied. Although this system is of little relevance, it could be expanded with relevant hardware
New Brunswick	No. 12 Bathurst	Lead-Zinc-Silver Copper	Stress fracturing or Stress Induced Slabbing	Type 271 accelerometers 80Hz-8kHz underground	Cable pairs		Electro-lab 256MP 32 channel				Used for source location and event rate counts	Ernstof et. al., (1987)	The capture of full waveforms is relevant otherwise is of little relevance
Ontario	Denison		Rockbursts	Physical Acoustic Corporation type p30D 50-400kHz underground 2-250kHz triaxial geophones underground 5 triaxial 8-300kHz geophones surface	Coaxial Cable	Pre Amplified Additional Power Amplifier	Microcomputer 12 bit A/D converter			Time and frequency domain calculations. Pattern recognition	No significant precursory behaviour	Calder et. al., (in press). Hedley, (in press)	Such a system could be deployed in development drivages. The software is also considered to be applicable to the coalfield
Ontario	Quirke	Uranium	Rockbursts	2-250kHz triaxial geophones 5 triaxial sets 8-300kHz geophones	Screened cable	Pre Amplified Surface conditioning and filtering	Electro-lab 256MP		Linear equation		Achieved automatic identification and location of events	Hedley, (1987). McDonald, (1982)	Unlikely to be of use without major modifications to both hardware and software
Saskatchewan	Cory	Potash	Mining activity and failure of carbonate rocks	16 geophone array initial 200m separation underground			Electro-lab 256MP Link IBM PC Electro-lab 500MP, IAM system™		SIMPLEX			Vance and Hattahead, (1989)	The system is limited by hardware. Although the IAM system™ has many features that should be used in a system for the Sydney Coalfield
Saskatchewan	Rocanville	Potash		Terra Technology DCS recorders and geophones underground			Apple II		SIMPLEX			Vance and Hattahead, (1989)	Equipment slow and difficult to use and has limited applicability and would not be recommended.
Saskatchewan	Esterhazy K1 and K2	Potash		Mark Products L-1 geophones underground	Cable	Frequency Modulation	Microseis 16 channel expandable to 32 channel Microseis II 32 channel	STA/LTA	SIMPLEX			Gendzwill and Prugger, (in press)	This represents one of the systems that would be applicable to the coalfield, although limited by the number of channels
Ontario	Elliot Lake			Originally Terra Dynamics APD-711 replaced by standard geophones surface broad band accelerometers underground	Fibre optics	Multiplexed	Nascomp DX 5400 Electro-lab 256MP	four point moving average	SIMPLEX CAMPLOC	Source parameters		Leluk and Mumah, (1987)	Although a purely surface based system it embodies many essential attributes and is of relevance to the coalfield
Sudbury Basin Ontario	Monitors the mines of INCO Ltd and Falconbridge Ltd			teledyne - geotech S13, with 50Hz package surface	Telephone lines	12 bit A/D converter	PDP 11/73, Microvax II	STA/LTA	Location Programme LOC	Source parameters can be calculated		Hedley and Udd, (1987) Plouffe et. al., (in press)	It would be difficult to install such a system, although the concepts are sound
Ontario	Quirke	Uranium	Rockbursts	Triaxial IDE 711 accelerometers. Replaced by Geospace GS-40B surface	Fibre Optics	Frequency Modulated and multiplexed	Electro-lab 256MP for location	Pre-set threshold on 5 sites		Source parameters determined		Semadeni et. al., (in press)	This has many applicable features although it is unlikely to be used as it stands
Saskatchewan	Cory	Potash	Mining activity and failure of carbonate rocks	Terra Technology transducers and recorders Mark Products L-1 geophones			Apple II - plus		SIMPLEX			Prugger and Gendzwill, (in press) Gendzwill and prugger, (in press)	Slow and difficult to use by todays standards and consequently would not realistically be recommended
Ontario	Denison Copper Cliffe North Mine Denison						COMPUTER SCOPE - IBD Digitising board with software running on a Zenith then on a Compaq portable II	Selectable trigger level and rising and falling slopes		Suite of time and frequency domain computations including pattern recognition		Teo, (1987)	
				Triaxial sets			IBM computer, Microvax			Full suite of full waveform processing and pattern recognition		Young, (1987a)	
Ontario	Strathcona	Nickel		5 clusters of triaxial sensors accelerometers 16 single component sensors	Cable	Electro-lab Model a27 Dual Gain Amplifier	Two Zenith 151 Electro-lab 256MP	Trigger logic unit based on signal level, duration and number of channels	Least squares				
North Western Quebec	East Malartic		Rockbursts	10Hz geophones	Cable	Pre Amplified	8MB digital micro-processor		Generated Block method. p-wave Direct Solution p-wave Least Squares Method		Some rockbursts occurred with precursors and some occurred with no precursory warning	Bourbonnay, (1986)	The methodology in part seems applicable. It would, however, require different hardware and software

Golder Associates

U.S.A.				SYSTEM					PROCESSING				
Region	Mine	Resource	Application	Transducers	Transmission System	Conditioning	Recording/Processing Hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
Idaho	Galena		Stope monitoring	16 geophones per stope expanded to 32 per stope underground, short period seismograph, surface	To surface by fibre optic cable		Underground computer					Bolstad, (in press)	Whilst this system is based on a good philosophy some re-designing would probably be required to be applicable
Idaho	Galena		Rockburst	Triaxial geophone sets 210/220, surface. Geophones mine wide, underground. Local system geophones, underground		Buffered pre-amplified analogue signal	Helicorder analogue recording					Brady, (1987)	Such a three dimensional system is relevant, although this as is stands may not be applicable
Idaho	Galena			Accelerometers, underground	Cable		Analogue tape recording					Leighton and Blake, (1970)	High frequency systems are only applicable in specific areas
Colorado	Deep coal mines	Coal	Coal bounces Roof falls	Geophones, underground			RBM					Leighton and Steblay, (1975)	High frequency systems are only applicable in specific areas
Idaho	Star	Lead-Zinc	Rockbursts				24 channel microcomputer based				Occasional seismic precursors to bursts. Bursts without precursors and precursors without bursts	Langstaff, (1977) Blake, (1984a)	Such high frequency systems are only applicable in specific areas, such as drivages
Michigan	White Pine Copper	Copper	Roof falls								When precursory activity was noted a fall occured soon afterwards	Gibbons, (1980)	Although there is limited information it clearly showed precursory activity.
	U.S.B.M.	Coal	Outbursts	Transducers composed of Lithium Sulphate crystals, underground	Cable to DAU Cable or telemetry	Pre-amplified	Data Acquisition Unit (DAU) Printers	Envelope detector Threshold triggering			Demonstrable precursors before outbursts	Leighton, (1984a) Leighton, (1984b)	High freqency systems are only relevant to specific areas as a consequence of high attenuation
Virginia	Kitt No. 1	Coal	Coal Bumps Roof Falls								Much further work required to obtain consistent results	Leighton, (1985) Erwin, (1989)	Such high frequency systems are only relevant in specific areas and if utilised would require frequent redeployment
Idaho	Star Lucky Friday	Lead-Silver-Zinc		Geophones, underground	Cable	Pre-amplified	RBM IMB system/7		Least squares			Hardy, (1987a)	This system would appear to be applicable although many more transducers would be required.
	U.S.B.M.	Coal	Roof Falls	Single Channel, underground			Integrated Sciences system				Provided an early warning for 20 out of 23 failures	Hardy, (1987a)	It is unclear whether this could predict outbursts and is unlikely to be recommended except in special circumstances
Utah, Gentry Mountain		Coal		Analogue and digital seismograph, surface								Wong et. al., (in press)	A high resolution three dimensional network is essential to the development of a system
Idaho	Lucky Friday	Lead-Silver-Zinc		34 geophones triaxial accelerometers, underground				Threshold triggering	Least squares			McWilliams et. al., (in press)	This system appears to be useful for the Sydney Coalfield although restricted in terms of frequency and detection pre requisites
		Coal		15 geospace type GSC-11D geophones, underground		Pre and post amplifiers	FM recorder and visicorder		Travel time difference method			Hawrey and Hardy, (1978)	Good philosophy of installing three dimensional arrays throughout the environments which should be utilised.
Paradox Basin	Book Cliffs	Coal	Monitor seismicity associated with mining	Short period seismometers, surface							Seems to be effective producing good results.	Wong (1984), Wong (1985)	Such a system would be difficult to install in the Sydney Coalfield

Golder Associates

TABLE A1 / 3

Golder Associates

UNITED KINGDOM				SYSTEM					PROCESSING				
Region	Mine	Resource	Application	Transducers	Transmission System	Conditioning	Recording/Processing Hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
Dyfed Wales	Cynheidre	Anthracite	Outbursts	Accelerometer, Underground Geophones, Underground	Cable FM Telemetry Cable		Portable Tape Recorder	Threshold		Frequency Analysis	Successfully recorded outbursts. Works well and reliably shows correlation between activity and methane emission	Hughes, (1973) Brown and McDonald, (1984) Rigby and Wardle, (1984) Rigby and Bolt, (1989)	The equipment used is out of date and would not be recommended. This could form the basis of a system for the Sydney Coalfield if expanded using state-of-the-art equipment and a full suite of the necessary software
Staffordshire	North Staffs. Coalfield	Coal	Earthquakes associated with mining	Seismometers, Surface	Telemetry				HYPO71 SIMPLEX		Successfully recorded events associated with collapse of the waste	Westbrook et. al., (1980; Kuznir et. al., (1980, 1982, 1984) Kuznir and Farmer, (1983)	Whilst this proved successful it could in itself not be used although a surface element should be part of a system
Dyfed Wales	Cynheidre	Anthracite	Outbursts	Seismometers, Surface	FM Digital Telemetry	None	University College of Swansea. Micro processor ICL 2900 VAX 8700 Digital cassette recorder	STA/LTA	HYPO71 SIMPLEX Least Squares	Time and frequency domain analysis source parameters	Successfully recorded outbursts and predicted outburst conditions	Davies et. al., (1987) Styles et. al., (1987a, 1987b, 1988, 1990)	Whilst predicting outburst conditions, a surface system would be difficult to establish but should form part of the overall system.
WEST GERMANY				SYSTEM					PROCESSING				
Region	Mine	Resource	Application	Transducers	Transmission Type	Conditioning	Recording/Processing Hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
Ruhr	Radbod, Westfalen	Coal	Seam Reaction to destressing drilling in outburst conditions	12 geophones, underground	Cable					Frequency Analysis	Effective in monitoring seam reaction to destressing drilling	Will, (1984a)	The basic components are applicable to the Sydney Coalfield
Ruhr	Radbod, Westfalen	Coal	Longwall retreat operations, outburst conditions	16 geophones, underground	Cable	12 bit A/D	Digital Recording	Threshold		Maximum amplitude and energy content		Will, (1985)	The basic components are applicable to the Sydney Coalfield
Ruhr	Radbod, Westfalen	Coal	Outburst Conditions	32 geophones, HS-2 Geophones, underground	Cable	Pre-amplified multiplexed anti-alias filtered A/D converter PCM signal transmitted to surface	Nova 3D Microvax II Recorded on tape	Amplitude threshold	Algorithm incorporating dispersion	Time and frequency domain processing	Successful in monitoring seismic activity as designed	Will, (1989)	This system is applicable to the Sydney Coalfield
	Asse 2	Salt		Geophones, underground	Cable	12 bit A/D	Paper chart Digital tape recorder	Amplitude threshold	Ingalede's method			Nente et. al., (1989)	The system other than bandwidth does not seem applicable
	Asse	Salt	Pillar Evaluation	Single piezo-electric sensor, underground	Cable		Oscilloscope and tape recorder	Amplitude threshold				Durr and Meister, (1984)	Whilst this is a useful system it is unlikely to be applicable to the coalfield

Golder Associates

				SYSTEM					PROCESSING				
Region	Mine	Resource	Application	Transducers	Transmission System	Conditioning	Recording/Processing Hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
FRANCE													
Provence	Provence coalfield	Coal	Relationships between face advance and energy released per shift to identify outburst conditions								Investigations showed suitable criteria existed to classify outburst conditions	Dechelette et al., (1984) Revalor et. al., (1986)	This was developed for a specific purpose and is unlikely to be relevant
Provence	Provence coalfield	Coal	Coal Bump	4 - 7 geophones 8 - 12 geophones, underground and surface	Telephone cables FM Modulation, cable or radio telemetry	Band pass filtered Band pass filtered	On-line computer Continuous chart recorder, Tape recorder	Pre-set threshold Pre-set threshold			Based on energy release rate dangerous areas are detected on one panel	Revalor et. al., (in press)	This represents an ideal design philosophy which is relevant to the coalfield although this system is unlikely to be adequate
SWEDEN													
	Laisvall Boliden		Roof falls	9 geophones, Underground									
	Malmberget, Dannemora, Grängesberg	Iron ore	Rockburste	local geophone array							Increase in activity prior to roof fall	Krauland and Westerberg, (1977)	It is likely that this system would not be relevant
AUSTRALIA											Discriminated different types of events	Bäth, (1980)	Local arrays to monitor selected areas is relevant to the overall development of a system
	Mount Isa	Lead-Zinc and Copper	Rockbursts. Location of rocknoise	32-channel geophones, Underground							Many problems experienced in commissioning the system	Godson, Bridges and McKevenagh, (1980)	Whilst the methodology is applicable the system itself is probably not
New South Wales	West Cliff	Coal	Outbursts	Single channel. Geophone underground							Noted a reduction in activity prior to outbursts	McKevenagh and Enever, (1980)	Methodology of installing transducers at seam level is applicable, although a single channel system is unlikely to be applicable
	Leichardt and Metropolitan	Coals	Outbursts	Accelerometers, Underground							Enhanced activity preceding a quiescent period prior to an outburst	Grezi et. al., (1984)	Transducers installed at seam level is applicable although the system is probably not relevant
JAPAN													
Hokkaido	Oyubari Akabira	Coal	Monitoring during advance boring	2-channel, geophones, Underground								Nakajima et. al., (1984)	The system was designed for a specific purpose and does not appear to be relevant
Hokkaido	Sunagawa	Coal	"Rockbursts"	Geophones, Underground/surface					Hypocentral location	Full waveform studies including energy release	From the reported results it appears to be successful with accurate locations	Isobe, (1976.) Isobe et. al., (1976, 1977, 1979, 1980 and 1984)	This type of mine wide system is applicable although the system itself is unlikely to be relevant
Hokkaido	Horonai	Coal									Seems to have worked well detecting more than 20,000 events with local magnitude greater than -2.5	Sato et. al., (1989)	The methodology is applicable although not necessarily the system
Hokkaido	Sunagawa	Coal	Outburst	8 geophones, Underground/surface					Joint Hypocentral determination		It appears to work well monitoring activity associated with outbursts	Sato and Fujii, (1987)	The three dimensional nature of the system is applicable
Hokkaido	Hora...	Coal		Accelerometers or geophones, Underground and near surface geophones, surface		Built in Tokyo Sokushin OS 11B pre-amplifiers. Digitised at recording station	Standard magnetic tape recorder	Pre-set threshold	Interactive least squares			Sato and Fujii, (1988)	A three dimensional system with digitising and recording should be applied to the Sydney Coalfield
	Miike	Coal	Pure Coal Outbursts	12 seismometers, underground		Amplifiers, Filters, A/D Converters	Mini-computer					Kaneko et. al., (in press)	This sort of 3D coverage should be deployed within the coalfield
Hokkaido	Sunagawa Horonai Akabira	Coal	Rock or Coal and Gas Outbursts	Endevco Accelerometers, underground	Cable	Pre-amplifier	Juneyan/Endevco			Frequency Analysis	Recorded acoustic emissions pre, during and post outburst	Watanabe et. al., (1984)	Two channel system which is unlikely to be applied to the Sydney Coalfield

Golder Associates

TABLE A1/5

Golder Associates

				SYSTEM					PROCESSING				
CHINA													
Region	Mine	Resource	Application	Transducers	Transmission System	Conditioning	Recording/Processing Hardware	Triggering	Location	Signal Processing	Success	Reference	Relevance
	Hard rock mines Coal mines Kentougu	Coal	Stope failure Coal Bursts	Single channel portable A/E systems							Some increase in A/E prior to failure and others with no warning. Increase in activity pre coalburst	(1, (1989)	The use of single channel systems would not fulfil the requirements except in special circumstances
	Yangquan First	Coal	Relationship between acoustic emission and gas emission during drilling	Accelerometers			Dunegan Endevco 300 AE Monitor					Zhang et. al., (1987)	This system is specialised and unlikely to be relevant
INDIA													
	Kolar gold mines	Gold	Rockbursts used to delineate zones of high seismicity Monitoring smaller area	7 Geospace geophones, Surface 7 Geospace geophones, Underground								Subbaraou et. al., (1989)	The concepts of this system should be considered in the design of a system for the coalfield
Bharbad				Triaxial geophone on the surface. Series of geophones underground								Subbaraou et. al., (1989)	The use of triaxial transducers should be considered for use in a system for the coalfield although the system does not appear to be applicable
EASTERN EUROPE													
Czechoslovakia Ostrava-Karviná coalbasin	Doubrava	Coal		3 channel digital								Holub, (1985) Holub et. al., (1987)	The system may not be applicable although the concepts are
Czechoslovakia	Etanda	Coal		2 underground 4 on the surface								Rudajev et. al., (1985)	The system may not be applicable although the concepts are
Poland		Coal	Used for scheduling destressing programmes and warning of rockbursts and outbursts	Underground and surface mounted								Hardy, (1987a)	The concepts of surrounding the area is applicable to the coalfield
Poland		Coal		Multi-channel and portable single channel Bruel and Kjer 4340 accelerometers	Cable	Bruel and Kjer 2616 pre-amplifiers	Teledyndon MAS 24-4 tape recorder				Increase in microseismic activity for several hours preceding major rockbursts	Trombik and Zuberek, (1977)	The methodology of deploying transducers throughout the mining levels is relevant to the coalfield although the systems may not be
Poland		Coal	Evaluate effects of destressing	geophones underground			Multi-channel tape recorder					Trombik and Zuberek, (1980)	This system was designed for a specific purpose and is unlikely to be relevant to the coalfield

Golder Associates

LIST OF REFERENCES

Antsyferov, M.S., 1966. Seismo-acoustic methods in mining. Consultants Bureau, New York.

Baria, R., Hearn, K. and Batchelor, A. S., 1989. The monitoring of the induced seismicity during the hydraulic of the potential hot dry rock geothermal reservoir. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, Hardy (ed), 1985, Trans Tech Publications, pp. 327-352.

Båth, M., 1980. A rockburst research project at Uppsala. In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 89-94.

Baule, H., 1977. Rockburst Geophysics - Seismoacoustic Determination for Destressing Burst Origins in the Advance Field of a Seam. Gluckauf, 7, pp. 360-362.

Baule, H., and Rao, M. V., 1979. Seismic Acoustic Activity in a Coal Seam in Relevance to Destressing, Rock Mechanics, vol. 11, pp. 177-187.

Blake, W., 1977. Design, installation and operation of computer controlled rock burst monitoring systems. In: Proceedings of the First Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1975, Hardy and Leighton (eds), Trans Tech Publications, pp. 157-168.

Blake, W., 1984a. Evaluation of some rockburst precursor phenomena. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 239-250.

Blake, W., 1984b. Design Considerations for Seismic Monitoring Systems. In: Proceedings of the First International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, Gay N. C., and Wainwright, E. H. (eds).

Blake, W., 1987. Microseismic Instrumentation. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal 1987, pp. 1-2.

Blake, W. F., and Leighton, F., 1970. Recent developments and applications of the microseismic method in deep mines, Proceedings 11 Symp on Rock Mechanics, (Berkeley 1969), AIME New York, pp. 429-443.

Bolstad, D. D., (in press). Rockburst Control Research by the U.S. Bureau of Mines. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Bourbonnais, J., 1984. A research application of multi-channel microseismic monitoring to rockbursting at the East Malarctic Mine in Northwerstern Quebec. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 252-268.

Brady, B. T., 1987. Microseismic/Rockburst research at the Galena mine, USA: a perspective. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 141-158.

Brown, K. M. and McDonald, P., 1984. A microseismic study of an outburst-prone coal seam. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 479-497.

Broz, M., 1975. Practical Experience with the Application of the Seismoacoustic Method for the Investigation of the Blasting Effects in View of the Application Possibilities of Induced Rock Firing. Acta Montana, vol. IV, no. 32, pp. 141-152.

Brune, J. N., 1970. Tectonic stress and the spectra of seismic shear waves from earthquakes. J. Geophs. Res., 75, pp. 4997-5009.

Buchheim, W., 1958. Geophysical methods for the study of rock pressure in coal and potash salt mining. In: Proceedings of the International Strata Control Congress, Leipzig, DDR, pp. 222-233.

Calder, P. N., Archibald, J. F., Madsen, D., and Bullock, K., (in press). High Frequency Precursor Analysis Prior to a Rockburst. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

CANMET, 1987. Development of an Outburst Model for the Sydney Coalfield. Report, DSS Contract No. 23440-6-9025 by Golder Associates.

Casten, U., and Cete, A., 1980. Induzierte Seismizitat im Bereich des Steinkohlenbergbaus des Ruhrreviers. Gluckauf-Forschungshefte, vol. 41, pp. 2-5.

Cete, A., 1977. Seismic Source Location in the Ruhr District. In: Proceedings of the First Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1975, Hardy and Leighton (eds), Trans Tech Publications, pp. 231-241.

Cook, N. G. W., 1976. Seismicity associated with mining. In: Induced Seismicity. Milne, W.G., (ed), Eng. Geol., 10, pp. 99-122.

Crampin, S., 1987. Geological and Industrial Implications of Extensive Dilatancy Anisotropy. Nature, vol. 328, pp. 491-496.

Davidge, G. R., 1987. Rockburst Research at Falconbridge Limited. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 189-217.

Davies, A. W., 1980. Available defences against outbursts in the United Kingdom in 1980. In: The occurence, prediction and control of outbursts in coal mines. Symposium Southern Queensland Branch of the Australian Institute of Mining and Metallurgy, Brisbane, Australia, Sept. 1980, AIMM; pp. 203-215.

Davies, A. W., Styles, P., and Jones, V. K., 1987. Developments in Outburst Prediction by Microseismic Monitoring from the surface. Mining Engineer, vol. 147, pp. 486-498.

Dechellette, O., Josien, J. P., Revalor, R. and Jonis, R., 1984. Seismo-acoustic Monitoring in an Operational Longwall Face with a high rate of advance, In: Rockbursts and Seismicity in Mines, S.A.I.M.M., 6, Gay and Wainwright (eds), pp. 83-87.

Dlouhy, L., 1976. Gephysical Instrumentation Equipment in Mines of the Ostrava-Karvina Coal Field. Acta Montana, Hornicky ustav CSAV, Cislo 38, pp. 237-254.

Dobecki, T., 1989. Acoustic emissions from hydraulic fractures in gas wells-Long term observations. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp 403-415.

Durr, K. and Meister, D., 1984. Evaluation of pillar deformation and stability in a salt mine utilising acoustic emission mine survey and rock deformation data. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 283-302.

Ersavci, M. N., 1989. Recent studies relevant to the Application of the McPhar Rock Stress Monitor. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 145-158.

Forgeron, S., et. al., 1986. The effects of Geological features on Coal Mining, Sydney Coalfield, Nova Scotia; Can. Inst. Min. Metal. Bulletin, vol. 79, No. 891.

Gendzwill, D. J., 1984. Induced seismicity in the Saskatchewan Potash Mines. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (eds), S.A.I.M.M., 6, pp. 131-146.

Gendzwill, D. J., and Prugger, A. F., 1987. Seismic Studies in Saskatchewan Potash Mines. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 329-337.

Gendzwill, D. J., and Prugger, A. F., 1989. Algorithms for Micro-Earthquake Locations. In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 601-615.

Gendzwill, D. J., and Prugger, A. F., (in press). Seismic Activity in a Flooded Saskatchewan Potash Mine. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Gibbons, M. G., 1980. Low frequency microseisms in relation to Mine roof stability. In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 245-258.

Gibowicz, S. J., 1984. The Mechanism of large mining tremors in Poland. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (Eds), S.A.I.M.M., 6, pp. 17-28.

Gibowicz, S. J., (in press). The Mechanism of Seismic Events Induced by Mining: A Review. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis 1988.

Godson, R. A., Bridges, M. C., and McKavanagh, B. M., 1980. A 32-Channel Rock noise source location system. In: Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 117-161.

Grezl, K. J., Leung, L., and Ahmed, M., 1980. Microseismic monitoring for gas outbursts at Leichardt colliery. In: The occurrence, prediction and control of outbursts in coal mines. Symp. Southern Queensland Branch of the Australasian Inst. of Mining and Metallurgy, Brisbane, Australia, 1980. Parkville, Australia, AIMM, pp. 15-158.

Grezl, K. J., Leung, L., and Ahmed, M., 1984. Development of Seismoacoustic Monitoring Techniques for Underground Mines in Austrailia. In: Proceedings of the Third Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Trans Tech Publications, pp. 347-364.

Hahnekamp, H. G., 1984. A simplified 4-Channel Microseismic Monitoring System. In: Proceedings of the Third Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Pennsylvania State University, 1981, Trans Tech Publications, pp. 659-670.

Hanson, D., Rochon, P., and Semadeni, T., 1987. Seismic Monitoring Systems Being Used in the Canada/Ontario/Industry Rockburst Project. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 159-168.

Hardy, H. R. Jr., 1980. Stability monitoring monitoring of and underground gas storage reservoir, In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 331-358.

Hardy, H. R. Jr., 1982. Applications of Acoustic Emission Techniques to Rock and Rock Structures: A State-of-the-Art Review. Special Technical Publication 750, American Society for Testing and Materials.

Hardy, H. R. Jr., 1984a. Geotechnical Applications of Acoustic Emission Techniques: Present Status and Future Goals. Seventh International Acoustic Emission Symposium, Sendai, Japan.

Hardy, H. R. Jr., 1984b. Stability monitoring of underground structures using acoustic emission techniques. In: Rockbursts and Seismicity in Mines', Gay and Wainwright (eds), S.A.I.M.M., 6, pp. 277-286.

Hardy, H. R. Jr., (in press 1986). Theory and Application of Acoustic Emmision/Microseismic Techniques. Trans Tech Publications.

Hardy, H. R. Jr., 1987a. A Review of International Research Relative to the Geotechnical Field Application of Acoustic Emission/Microseismic Techniques. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 69-114.

Hardy, H. R. Jr., 1987b. Field Orientated Geotechnical Acoustic Emission/Microseismic Research at the Pennsylvania State University. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 287-306.

Hardy, H. R. Jr., and Mowrey, G. L., 1976. Study of microseismic activity associated with a longwall coal mine operation using a near surface array. Proceedings First Inter. Symp. Induced Seismicity, Jour. Eng. Geol., 10, pp. 263-281.

Hardy, H. R. Jr., and Mowrey, G. L., 1984. Analysis of Microseismic Data from a Natural Gas Storage Reservoir. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 365-392.

Hedley, D. G. F., (in press). Peak Particle Velocity for Rockbursts in Some Ontario Mines. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Hedley, D. G. F., Bharti, S., West, D. and Blake, W., 1989. Fault-slip rockbursts at the Falconbridge Mine. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 159-170.

Hedley, D. G. F., and Udd. J. E., 1987. The Canada-Ontario-Industry Rockburst Project. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 115-127.

Hente, B., Quijano, A., and Durr, K., 1989. Microseismic observations in a salt mine with reference to the mine survey results. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 171-179.

Hirota, T., Watanabe, Y., Seisho, M., and Higuchi, K., 1983. Disaster of coal and gas outbursts at Yubari Shin Colliery. In: Proceedings of the 20th International Conference of Safety in Mines. Research Institutes, Sheffield, UK, 3-7 Oct 1983. Health and Safety Executive, Translation Service; Paper B5, 14pp.

Hodgson, E. A., 1958. Dominion Observatory Rockburst Research 1938-1945, Dept. of Mines and Technical Surveys, Canada, Dominion Observatories, p 20.

Holub, K., 1985. Study of Microseismic Activity Associated with Mining. Proceedings of the 3rd International Symposium on The Analysis of Seismicity and Seismic Risk, Liblice Castle, Czechoslovakia, 1985, pp. 160-164.

Holub, K., Korinek, J., Kalenda, P., Slavik, J., and Schreiber, P., 1987. Recent developments and applications of microseismic methods in conditions of the rockburst hazard in the Ostrava-Karvina Coal Basin, Czechoslovakia, 22 Int. Conference Safety in Mine Research, Beijing, China, Dai Guoquang (ed), pp. 259-274.

Hughes, J. E. T., 1973. Outbursts of coal and gas of the anthracite area of S. Wales. MSc thesis, University of Wales, Cardiff.

Isobe, T., 1974. Measurements of seismic waves causd by underground ectraction of coal seams, Proceedings of the 3rd ISRM Congress, Denver, Vol II, Part B, pp. 1278-1282.

Isobe, T., Mori, N., and Fukushima, A., 1976. Further investigation on the problems of underground Rock destruction by using seismic method, Proceedings of the 4th ISRM, Sydney, pp. 50-54.

Isobe, T., Mori, N., Ishijima, Y., and Fukushima, A., 1976. Measuremnts and analysis of ground tremors caused by working coal seams, 6th International Conference on Strata Control, Canada, Paper 10.

Isobe, T., Mori, N., Sato, K., Goto, T., 1979. Development and application of computer system for monitoring seismicity induced by underground coal mining. In: Application of computers abd operations research in the mineral industry, O'Neill (ed.), AIME, New York, pp. 513-527.

Isobe, T., Mori, N., Sato, K., Goto, T., 1980. Measurement and analysis of seismic events in deep level coal mines. In: The occurrence, prediction and control of outbursts in coal mines. Symp. Southern Queensland Branch of the Australasian Inst. of Mining and Metallurgy, Brisbane, Australia, Sep. 1980. Parkville, Australia, AIMM, pp. 127-138.

Isobe, T., Sato, K., Mori, N., and Goto T., 1984. Microseismic Activity Induced by Hydraulic Mining of Steeply inclined Coal Seams. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 403-424.

Jackson, L., 1984. Outbursts in Coal Mines. I.E.A., Coal Research, Report No.: ICTIS/TR25.

Jackson, P., 1989. Measuring seismic wave polarisations, European Association of Exploration Geophysicists, Berlin 1989, 205, 1, 317.

Kaneko, K., Sugawara, K., and Obara, Y., (in press). Rock Stress and Microseismicity in Coal Burst District. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Knill, J. L., Franklin, J. A., Malone, A. W., 1968. A study of acoustic emission from stressed rock. Intnational Journal Rock Mechanics and Mining Sciences and Geomechanical Abstracts, Vol.5, pp. 87-121.

Kozlowski, B., 1983. Opening up and development of seams prone to sudden outburst. In: Proceedings of the 20th International Conference of Safety in Mines. Research Institutes, Sheffield, UK, 3-7 Oct 1983. Health and Safety Executive, Translation Service; Paper B7, 15pp.

Krauland N, and Westerberg K, 1977. Experiences with AE measurements in Boliden Mines. In: Proceedings of the First Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1975, Hardy and Leighton (eds), Trans Tech Publications, pp. 195-204.

Kristof, B., MacDonald, T., and Landry, G., 1987. The Microseismic Monitoring System at Brunswick Mining and Smelting Corporation Ltd #12 mine, Bathurst, New Brunswick. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 245-256.

Kuznir, N. J., Farmer, I. W., Ashwin, D. P., Bradley, L. G., and Al-Saigh, N. H., 1980. Observations and mechanics of seismicity associated with coal mining in North Staffordshire, England. In: Proceedings of 21st U.S. Symp. on rock mechanics, University of Rolla, Missouri, 27 May 1980, pp. 632-640.

Kuznir, N. J., Al-Saigh, N. H., and Farmer, I. W., 1982. Proceedings Symp. Strata Mech., Newcastle-upon-Tyne, Developments in Geotechnical Engineering, Farmer (Ed.) 7-12 (Elsevier, Amsterdam).

Kuznir, N. J., and Farmer, I. W., 1983. Rockburst phenomena in British Coal Mines. In: Rockbursts: prediction and control. Symp. I.M.M., London, U.K., 20 October 1983, pp. 103-115.

Kusznir, N. J., Al-Saigh, N. H., and Ashwin, D. P., 1984. Induced seismicity generated by long-wall mining in the North Staffordshire coal-field, U.K. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (Eds), S.A.I.M.M., 6, pp. 153-160.

Labuc, V., Bawden, W., and Kitzinger, F., 1987. Seismic monitoring systems using fibre-optic signal transmission. Proceedings 6th International Rock Mechanics Congress. Montreal.

Labuc, V., and Momoh, O. A., 1987. The CANMET-Noranda Seismic Monitoring System Using Fibre Optic Signal Transmission. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 237-244.

Langstaff, J. T., 1977. Hecla's rockburst monitoring system, Mining Congress Journal, pp. 45-51.

Leighton, F., 1984a. Microseismic activity associated with outbursts in coal mines. In: Proceedings Third Conference on AE/MS activity in Geol. Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 467-477.

Leighton, F. J., 1984b. Microseismic Monitoring and warning of Rockbursts. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (eds), S.A.I.M.M., 6, pp. 287-296.

Leighton, F., 1985. An automated real-time coal mine bump monitor. Abstracts of the proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy and Leighton (eds), Trans Tech Publications.

Leighton, F. J. and Blake, W., 1970. Rock noise source location techniques, USBM R.I. 7432, 14pp.

Leighton, F. and Steblay, B. J., 1975. Coal mine bounce and roof fall research. Proceedings First Conference Underground Mining (Louisville 1975), 11, pp. 104-119.

Li, D., 1989. Application of AE techniques to prediction of mining structure failures. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 181-187.

Lingle, R. and Francis, G. G., 1980. Acoustic emission monitoring at Coalville, Utah. In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 359-373.

MacDonald, P., 1982. Microseismic Monitoring at New Quirke Mine. CANMET, Minerals Research Laboratories Division Report, MRP/MRL 83-14 (TR).

Makuch, A., 1987. Rock Mechanics at Campbell Red Lake Mine. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal 1987, pp. 181-188.

Matuzewski, J., 1980. Exploration of coal deposits under Hazardous conditions. In: Seminar on Improved Techniques for the Extractionn of Primary Forms of Energy, Vienna, Austria, 10-14 Nov. 1980. United Nations Economic Commission for Europe; 22pp. (1980) ECE/SEM.4/R.19.

McDonald ,P., and Cochrane, L., 1987. Research related to mining induced seismicity at INCO Limited. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 219-225.

McKavanagh, B. M., Enever, J. R., 1980. Developing a microseismic outburst warning system. In: Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 211-225.
McMechan, G. A., 1983. Seismic Tomography in Boreholes. Geophysical Journal Royal Astronomical Society, vol. 74, pp. 601-612.

McWilliams, P., McDonald, M., Jenkins, M., (in press). Statistical Analysis of a Micro-seismic Field Data Set. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Meister, D., 1980. Microacoustic studies in rock salt. In: Proceedings of the Second Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), Trans Tech Publications, pp. 259-275.

Momoh, O. A., Bawden, W. F., and Kanduth, H., 1989. AE/MS Monitoring in Noranda Group Mines. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials 1985, Hardy (ed), Trans Tech Publications, pp. 189-205.

Mottahead, P., and Vance, J. B., 1987. MA/AE research at PCS Mining operations in Saskatchewan, Canada. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 257-263.

Mowrey, G. L., and Hardy, H, R, Jr., 1978. Microseismic Activity Associated with Longwall Coal Mining. AIME Annual Meeting Denver, Colorado.

Nakajima, I., Watanabe, Y., and Fukai, T., 1984. Acoustic Emission during advance boring associated with the prevention of coal and gas outbursts. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 529-548.

Neumann, M., and Makuch, A. P., 1989. Analysis of Microseismic Activity Prior to Pillar Rockburst in Campell Red Lake Mine F-2 Zone. In: Proceedings of the Fourth Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed) Trans Tech Publications, pp. 225-240.

Niewiadomski, J., 1987. Source Location Techniques for Seismic Activity in Mines. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 5-21.

Niitsuma, H., Takanohashi, M., Chubachi, N. and Yokohama, H., 1989. Downhole AE measuremnt of a geothermal reservoir and its application to reservoir control. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 475-489.

Obert, L., 1941. Use of sub-audible noises for prediction of rock bursts, USBM, Rep. of Investigations, No. 3555, 4p.

Obert, L., and Duvall, R., 1942. Use of sub-audible noises for the prediction of outbursts, Part II., U.S. Bureau of Mines. Report R13154.

Oliver, P., and McDonald, P., 1989. The microseismic monitoring system at Creighton Mine, Inco Ltd. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 241-248.

Pakalnis, V., 1984. Strengths and limitations of Microseismic monitoring for rockburst control in Ontario Mines. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 549-558.

Pearson, C., and Albright, J. N., 1984. Acoustic emissions during hydraulic fracturing. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 559-575.

Peter, A., and Pellionisz, P., 1980. Research and Development of Acoustic Emission Techniques in Hungary. Conference on On-Line Surveillance and Monitoring of Plant Reliability, Imperial College, London, September 1980, pp. 53-61.

Peter, A., and Pellionisz, P., and Gereb, J., 1981. Acoustic Emission Research at the Central Research Institute of Physics (KFKI) of the Hungarian Academy of Sciences, Meres es Automatika, XXIX, pp. 392-395.

prugger, A. F., and Gendzwill, D. J., 1983. Earthquake monitoring system used at the PCS Mining, Cory Division potash mine near Saskatoon, Canada. In: Potash Technology, McKercher, R. M., (ed). Pergamen Press, pp 191-196.

Prugger, A. F., and Gendzwill, D. J., (in press). Results of Micro-seismic Monitoring at the Cory Mine, 1981 - 1984. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Plouffe, M., Cajka, M. G., Wetmiller, R. J., and Andrew, M. D., (in press). The Sudbury Local Telemetered Seismograph Network. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Quesnel, W. J. F., Hong, R., 1987. Mining Induced Seismicity: Monitoring and Interpretation. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 227-235.

Reinhard, M., 1955. Study by geophysical methods of Earth tremors caused by Shots and outbursts, Revue de L'Industrie Minerale.

Reinhard, M., 1956. Use of geophysical methods and remote indicating firedamp detectors in an outburst deposit. Revue de L'industrie Minerale.

Revolar, R., Dechellette, O. and Verstraete, M., 1986. Detection of coal-bump risk using seismo-acoustic Monitoring at the probence Collieries. Min. Sci. Tech, 4, pp. 11-23.

Revolar, R., Josien, J. P., Besson, J. L., and Magron, A., (in press). Seismic and Seismo-acoustic Experiments Applied to the Prediction of Rockbursts in French Coal Mines. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Rigby, N. and Wardle, J., 1984. Microseismic monitoring and outburst prediction, Proceedings 15th Ann. Inst Coal Mine Health, safety and Research, Blacksburg, Virginia.

Rigby, N. and Bolt, P. B., 1989. Development and application of an underground microseismic monitoring system for outburst prone coalmines, The Mining Engineer. November 1989, pp. 197-203.

Roberts, I., 1983. The effects of outbursts of coal and gas on deep mining in the Bowen Basin, Queensland and the efforts made to deal with the Phenomena. Part 3: the development of predicitive methods. Queensland Government Mining Journal; 84 (975); pp. 12-19.

Roček, V., Rudajev, V., and Polach, V., 1975. Problems of Occurrence of Rock Bumps Within the Bituminous Coal. Acta Montana, Hornicky ustav CSAV, Cislo 32, pp. 185-198.

Rudajev, V., and Sileny, J., 1985. Seismic events with non-shear components: II. Rockbursts with an implosive source component, Pageoph, vol. 123, pp. 17 - 25.

Sato, K., and Fujii, Y., 1987. Seismicity associated with a large scale outburst. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 277-286.

Sato, K., and Fujii, Y., 1988. Induced Seismicity Associated with Longwall Coal Mining. International Journal Rock Mechanics Mining Sciences and Geomechanical Abstracts, vol. 25 no. 5, pp. 253-262.

Sato, K., Fujii, Y., Ishijima, Y., Kinoshita, S., 1989. Microseismic activity induced by Longwall Coal Mining. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials 1985, Hardy (ed), Trans Tech Publications. pp. 249-263.

Semadeni, T. J., and Calder, P. N., (in press)a. High Frequency Micro-seismic Monitoring Applied to the Determination of Stress Levels in Hard Rock Mines. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Semadeni, T. J., Rochon, P., and Niewiadowski, J., (in press)b. Waveform Analysis of Mine-Induced Seismic Events Recorded at Rio Algom's Quirke Mine. Second International Symposium of Rockbursts and Seismicity in Mines, Minneaoplis, 1988.

Simane, J., 1963. The use os seismoacoustic method in investigations into rock bursts, 15 Mining and Metallurgy Day, Freiberg.

Simane, J., 1975. Effect of Exploitation Progress in a Stope and of the Mining Activities in its Neighbourhood on the stability of the Rock Mass in the Rockburst Exposed Areas of Ore Mines. Acta Montana, vol. IV, no. 32., pp. 139-137.

Shepherd, J., Rixon, L. K., and Griffiths, L., 1981. Outbursts and geological structures in coal mines, a Review. International Journal of Rock Mechanics and Mining Sciences and Geomechanical Abstracts; vol. 18, pp. 267-283.

Sombati, A., 1983. Brief Description of Recent Rock Mechanics Research Work in the Hungarian Mining Industry. Internal Report, RML-IR/83-2, Geomechanics Section, The Pennsylvania State University, University Park, Pennsylvania.

Stas, B., Dlouhy, L., Strabis, A., and Siska, L., 1971. Development Trends and Applications of Geophysical Research in Mines of the Ostrava-Karvina Coal Field, Proceedings of the Twelfth Symposium on Rock Mechanics, Rolla, 1970, AIME, New York, pp. 109-119.

Steinwachs, M., 1984. Mobile Telemetric Equipment for Digital Recording and Processing of Microseismic Activity. In: Proceedings of the Third Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Trans Tech Publications, pp. 591-599.

Styles, P. and Emsley, S. J. 1987a. Integrated microseismic monitoring and early warning system for outbursts of coal and firedamp, NCB/ECSC Research Contract YCE 28/17619:, Final Report.

Styles, P., Jowitt, T., and Browning E., 1987b. Surface Microseismic Monitoring for the prediction of Outbursts, 22 Int. Conference Safety in Mine Research, Beijing, China, Dai Guoquang (ed), pp. 767-780.

Styles, P., Emsley, S. J. and Jowitt, T. 1988. In: Engineering Geology of Underground Movements, Geol. Soc. Engineering Geology Special Publication, 5, pp. 423-433.

Styles, P., Emsley, S. J., and McInairnie, E. A., 1990. Outburst Prediction and Management Using Surface Seismic Monitoring. Geophysical Journal International, vol. 101, no. 1.

Subbarumu, K. R., Rao, B. S. S., Krishnamurthy, R., and Srinivsan, C., 1989. Seismic investigations monitoring of rockbursts in the Kolar Goldfields. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, Hardy (ed), Trans Tech Publications, pp. 265-274.

Talebi, S., Young, R. P., (in press). Characterizing Micro-seismicity Associated with Stope Development. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Trombik, M., and, Zuberek, W., 1977. Microseismic Research in Polish Coal Mines. Proceedings 1st Conference on AE/MS in Geol. Structures and Materials, Penn. State University, Hardy and Leighon (eds), pp. 169-194.

Trombik, M., and, Zuberek, W., 1980. Location of Microseismic Sources at the Szombierki Coal Mine. In: Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geological Sructures and Materials, 1978, Trans Tech Publications, pp. 177-180.

Udd, J. E., and Hedley, D. G., 1985. Rock Mechanics Research in the Mining Research Laboratories of CANMET, 1964-1984 - A submission to the Provincial Inquiry into Ground Control and Emergency Preparations in Ontario Mines. Division Report MRP/MRL 85-19(TR), Mining Research Laboratories, CANMET, Department of Energy, Mines and Resources, Ottawa.

Vance, J. B. and Mottahead, P., 1989. AE/MS applications to Potash Mining Problems. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 275-286.

Watanabe, Y., Nakajima, I., and Itakura, K., 1984. The Fracturing Activity Prior to Coal or Rock Outbursts in Cross Measures Drivages. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 613-632.

Westbrook, G. K., Kusznir, N. J., Browitt, C. W. A., and Holdsworth, B. K., 1980. Seismicity induced by coal mining in Stoke-on-Trent (UK), Engineering Geology, 16, pp. 225-241.

Will, M., 1980. Seismoacoustic activity and mining operations. In: Proceedings Second Conference on Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1978, Hardy and Leighton (eds), pp. 191-209.

Will, M., 1984a. Measurement and on-line evaluation of seismic seam reactions during test and destressing drilling. In: Proceedings of the Third Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1981, Hardy and Leighton (eds), Trans Tech Publications, pp. 633-646.

Will, M., 1984b. Seismic Observations during test drilling and destressing operations in German Coal Mines. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (eds), S.A.I.M.M., 6, pp. 231-234.

Will, M., 1984c. Monitoring of Seismic Events during Longwall Retreat Operations in German Coal Mines. In: Proceedings of the 1st Internatioanl Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, Gay, N. C., and Wainwright, E. H. (eds).

Will, M., Rakers, E., Klockmann, W., Rucker, W., 1985. Masnahmen Zurgebirgsschlagverhutung in steinkolenflozen. Bunders Ministerium fur Forschung und Technologie Forschungsbericht HA 85-008, 140 pp.

Will, M., 1989. Entwicklungen im Fachbereich Gebirgsschlag-Geophysik, W.B. K., Bochum, 15 pp.

Williams T. J., and Cuvelier, D. J., (in press). Report on a Field Trial of an Underhand Longwall Mining Method to Alleviate Rockburst Hazards. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Wong, I. G., 1984. Mining induced seismicity in the Colorado, western United States and its implications for the siting of an underground high-level waste repository. In: 'Rockbursts and Seismicity in Mines', Gay and Wainwright (Eds), S.A.I.M.M., 6, pp. 147-152.

Wong, I. G., 1985. Mining induced earthquakes in the Book Cliffs and Eastern Wasatch Plateau, Utah, U.S.A. International Journal of Rock Mechanics and Mining Sciences and Geomechanical Abstracts; vol. 22, no. 4, pp. 263-270.

Wong, I. G., Humphrey, J. R. and Silva, W., 1989. Microseismicity and subsidence associated with a potash solution mine, South-Eastern Utah. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 287-306.

Wong, I. G., and McGarr, A., (in press). Implosional Failure in Mining-Induced Seismicity: A Critical Review. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Yeo, T. K., 1987. Development of Microseismic Monitoring Software. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 319-326.

Young, R. P., 1989. Seismic Propagation in Rock Masses: Implications for AE/MS. In: Proceedings of the Fourth Conference Acoustic Emission/Microseismic Activity in Geological Structures and Materials, 1985, Hardy (ed), Trans Tech Publications, pp. 531-550.

Young, R. P., Hutchins, D. A., Talebi, S., Chow, T., Falls, S., Farrell, L., Jansen, D., McGaughey, J., Towers, J., and Urbancic, T., 1987a. Laboratory and Field Investigations of Rockburst Phenomena Using Concurrent Geotomographic Imaging and Acoustic Emission/Microseismic Techniques. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal 1987, pp. 307-318.

Young, R. P., Hutchins, D. A., McGaughey, J., Towers, J., Jansen, D., Bostock, M., 1987b. Geotomographic Imaging in the Study of Mining Induced Seimicity. Fred Leighton Memorial Workshop on Mining Induced Seismicity, Montreal, 1987, pp. 39-67.

Young, R. P., Hutchins, D. A., McGaughey, W. J., Urbancic, T., Falls, S., and Towers, J., 1987c. Concurrent seismic tomographic imaging and acoustic emission techniques: a new approach to rockburst investigations. Proceedings 6th ISRM Int. Congress on Rock Mechanics, Montreal, pp. 1333-1338.

Young, R. P., Hutchins, D. A., McGaughey, W. J., (in press). Seismic Imaging Ahead of Mining in Rockburst Prone Ground. Second International Symposium of Rockbursts and Seismicity in Mines, Minneapolis, 1988.

Zhang, W., Ma. F., Tu, X., Nakajima, I., Ujihira, M. and Ohga, K., 1987. The relationship between acoustic emission and gas emission due to coal mining operations. In: Proceedings 22nd Int. Conference Safety in Mines Research, Beijing, China, Dai Guoquan (Ed), pp. 135-146.